

JOURNAL OF
GEOPHYSICAL RESEARCH
The continuation of
TERRESTRIAL MAGNETISM AND ATMOSPHERIC ELECTRICITY
(1896-1948)
An International Quarterly

OLUME 61

June, 1956

NUMBER 2

(Part 2)

SPECIAL CONFERENCE SECTION

PROCEEDINGS OF THE WASHINGTON CONFERENCE ON

THEORETICAL GEOPHYSICS—1956, - - - - - 317-414

(Note: Contents of Part 1, No. 2, are listed on the cover of Part 1)

Part two of two parts, June, 1956

Published at

THE WILLIAM BYRD PRESS, INC.

P. O. Box 2-W, SHERWOOD AVE. AND DURHAM ST.
RICHMOND 5, VIRGINIA

Address all correspondence to

JOURNAL OF GEOPHYSICAL RESEARCH

5241 BROAD BRANCH ROAD, NORTHWEST
WASHINGTON 15, D.C., U.S.A.

SIX DOLLARS A YEAR

SINGLE NUMBERS, TWO DOLLARS

JOURNAL OF GEOPHYSICAL RESEARCH

The continuation of

Terrestrial Magnetism and Atmospheric Electricity (1896-1948)

An International Quarterly

Founded 1896 by L. A. BAUER

Continued 1928-1948 by J. A. FLEMING

Editor. MERLE A. TUVE

Editorial Assistant: WALTER E. SCOTT

Honorary Editor: J. A. FLEMING

Associate Editors

N. Arley, Polarvej 12,
Hellerup, Denmark

J. B. Hersey, Oceanographic Institution,
Woods Hole, Massachusetts

J. Bartels, University of Göttingen,
Göttingen, Germany

D. F. Martyn, Commonwealth Observatory,
Canberra, Australia

H. G. Booker, Cornell University,
Ithaca, New York

T. Nagata, Geophysical Inst., Tokyo Univ.,
Tokyo, Japan

B. C. Browne, Cambridge University,
Cambridge, England

M. Nicolet, Royal Meteorological Institute,
Uccle, Belgium

S. Chapman, Queen's College,
Oxford, England

B. F. J. Schonland, Atomic Energy Research
Establishment, Harwell, England

A. A. Giesecke, Jr., Instituto Geofisico,
Huancayo, Peru

M. S. Vallarta, C.I.C.I.C.,
Puente de Alvarado 71, Mexico, D. F.

J. T. Wilson, University of Toronto,
Toronto 5, Canada

Fields of Interest

Terrestrial Magnetism

The Constitution and Physical States of the
Upper Atmosphere

Atmospheric Electricity

Special Investigations of the Earth's Crust
and Interior, including experimental seismic
waves, physics of the deep ocean and ocean
bottom, physics in geology

The Ionosphere

And similar topics

Solar and Terrestrial Relationships

Aurora, Night Sky, and Zodiacal Light

The Ozone Layer

Meteorology of Highest Atmospheric Levels

This Journal serves the interests of investigators concerned with terrestrial magnetism and electricity, the upper atmosphere, the earth's crust and interior by presenting papers of new analysis and interpretation or new experimental or observational approach, and contributions to international collaboration. It is not in a position to print, primarily for archive purposes, extensive tables of data from observatories or surveys, the significance of which has not been analyzed.

Forward manuscripts to one of the Associate Editors, or to the editorial office of the Journal at 5241 Broad Branch Road, Northwest, Washington 15, D. C., U. S. A. It is preferred that manuscripts be submitted in English, but communications in French, German, Italian, or Spanish are also acceptable. A brief abstract, preferably in English, must accompany each manuscript. A publication charge of \$8 per page will be billed by the Editor to the institution which sponsors the work of any author; private individuals are not assessed page charges. Manuscripts from outside the United States are invited, and should not be withheld or delayed because of currency restrictions or other special difficulties relating to page charges. Costs of publication are roughly twice the total income from page charges and subscriptions, and are met by subsidies from the Carnegie Institution of Washington and international and private sources.

Back issues and reprints are handled by the Editorial Office, 5241 Broad Branch Road, N.W.
Washington 15, D.C., U.S.A.

Subscriptions are handled by the Editorial Office, 5241 Broad Branch Road, N.W., Washington 15,
D.C., U.S.A.

Journal of
GEOPHYSICAL RESEARCH

The continuation of

Terrestrial Magnetism and Atmospheric Electricity

VOLUME 61

JUNE, 1956

Number 2—Part 2
Special Conference Section

WASHINGTON CONFERENCE ON THEORETICAL GEOPHYSICS—1956

A conference on theoretical geophysics was held at the National Science Foundation in Washington, D.C., on February 1, 2, and 3, 1956, jointly sponsored by the National Science Foundation and the Carnegie Institution of Washington. The Steering Committee of the Conference appointed by the National Science Foundation comprised John von Neumann, chairman, E. H. Vestine, deputy-chairman, L. V. Berkner, J. Kaplan, H. K. Stephenson, NSF Liaison Representative, and J. G. Charney, secretary.

Over one hundred participants were invited because of their interest in the use of theoretical and mathematical approaches in the solution of geophysical problems, mainly in meteorology, oceanography, hydromagnetism, geomagnetism, aurora, cosmic rays, ionospheric physics, atmospheric electricity, geochemistry, seismology, gravity and geodesy, tectonophysics, and origin of the earth. Although the area of coverage was considerable, there were omitted important areas in which theory is useful, such as in the engineering applications to geology, ground water, and hydrology. The aims of the conference were described as those of obtaining a broad picture of the current status of knowledge of geophysics, and especially of that gained mainly by theoretical geophysics in this country and abroad, to encourage increased activity in theoretical geophysics, and to discuss future programs and opportunities. It was pointed out that the Carnegie Institution of Washington was glad to sponsor an examination of the status of research in this subject and of present and future needs, but was not placing itself in the position of urging the creation of new institutes. Actually, one immediate background motivation for the conference arose from needs for study of global aspects of geophysics, based on the world-wide observations of many nations during the International Geophysical Year. The early incidental background motivation was the expression of dissatisfaction in some quarters that only one or two people in this country were now active in theoretical studies of geomagnetism. Later,

weaknesses were noted in a number of other areas as well, with many interlinkages of theoretical interest throughout the whole range of geophysics.

The JOURNAL is indebted to the participants and to Dr. Jule G. Charney, Secretary of the conference, for the following summaries and abstracts. A subsidy from the special fund for the conference, which was provided by the National Science Foundation, has made it possible to publish these notes on the conference. The material which follows has been arranged chronologically in accordance with the conference program.

PROGRAM

Wednesday, February 1, 1956, 9:30 A.M.

Greetings by National Science Foundation and the Carnegie Institution of Washington

- H. Stommel: Oceanography
- C. Eckart: Geophysics
- J. G. Charney: Meteorology
- D. Fultz: Meteorology
- V. P. Starr: Meteorology
- W. M. Elsasser: Hydromagnetics
- S. Chandrasekhar: Hydromagnetics
- H. G. Booker: Ionosphere
- R. M. Gallet: Ionosphere
- L. V. Berkner: Ionospheric research, IGY

Wednesday, February 1, 1956, 2:00 P.M.

- S. Chapman: Ionosphere
- N. C. Gerson: Meterology
- J. W. Chamberlain: Aurora
- D. H. Menzel: Astrophysics
- W. H. Bennett: Aurora
- R. Gunn: Atmospheric physics
- H. R. Byers: Atmospheric physics
- S. E. Forbush: Cosmic rays
- J. A. Simpson: Cosmic rays
- E. H. Vestine: Geomagnetism
- A. G. McNish: Geomagnetism
- J. R. Balsley: Paleomagnetism
- S. B. Nicholson and O. R. Wulf: Geomagnetism

Wednesday, February 1, 1956, 8:00 P.M.

Members of working committees met as directed by Chairmen

Thursday, February 2, 1956, 9:00 A.M.

- H. E. Tatel: Tectonophysics
W. H. Bucher: Tectonophysics
F. Press: Seismology
L. B. Slichter: Seismology
B. Gutenberg: Seismology
M. Ewing: Seismology
J. Verhoogen: Tectonophysics
W. A. Heiskanen: Gravity
G. P. Woppard: Tectonophysics
H. S. Yoder: Tectonophysics
G. J. F. MacDonald: Tectonophysics

Thursday, February 2, 1956, 2:00 P.M.

- L. T. Aldrich: Age determination
H. E. Seuss: Age determination
J. Kaplan: International Geophysical Year
L. V. Berkner: Atmospherics
Reports of various committees and sub-committees on institute planning, on site, and on finance; discussion of reports

Thursday, February 2, 1956, 6:30 P.M.

Dinner at Ambassador Hotel, with after-dinner speakers:

- H. C. Urey: "Boundary conditions for the origin of the earth and planets"
G. P. Kuiper: "The origin of earth and planets"

Friday, February 3, 1956, 9:00 A.M.

- C. L. Pekeris: Seismology
R. Stoneley: Seismology
W. O. Roberts: Astrophysics
B. Gutenberg: Meteorology

Friday, February 3, 1956, 2:00 P.M.

- B. Gutenberg: International Geophysical Year
Informal discussions of uses of IGY world-wide data in the solution of geophysical problems
Actions and recommendations

Wednesday, February 1, 9:30 A.M.-12:55 P.M.

John von Neumann, Chairman

E. H. Vestine, Deputy Chairman

The conference was opened with welcomes by M. A. Tuve, for the Carnegie Institution of Washington, and by C. E. Sunderlin and Raymond J. Seeger, for the National Science Foundation.

HENRY STOMMEL, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts: **Oceanography.** The interrelationships of various branches of the geophysical sciences are likely to be more intimate in those vast areas of geophysical knowledge which are still unexplored, rather than in those areas which have already been explored. Indeed, this must be the case, because much of the success to date, in solving theoretical geophysical problems, has come from our natural tendency to select for study those very aspects of the earth's physical nature which are not interrelated in too complex a way.

In oceanography, we have been very selective of problems. Is the phenomenon well isolated from others? Are there readily available techniques for solving the theoretical model? Can we avoid having to deal with unpleasant and poorly understood physical processes like turbulence? I know very little about the other geophysical sciences, but I imagine much of the preoccupation with, for example, wave-phenomena, has its roots in these selective criteria. In trying to estimate the interrelatedness of general geophysics by comparing the problems we will today, we should make allowance for how much we tried to separate them.

The central problem of physical oceanography is the general circulation of the ocean. The dynamical framework of the β -plane, used in recent theoretical meteorological studies such as Phillips' numerical theory of the general atmospheric circulation, is probably equally applicable to the circulation of the ocean. The distribution of heat sources is different, of course, and the applied wind stress at the ocean surface is different from the surface stress condition in the atmosphere, but these appear from a point of view to be trivial differences. The essential difference between the general circulations of atmosphere and oceans is the existence of meridional barriers in the oceans, that is, the continental land masses. These barriers exclude, in the ocean, that class of solutions characteristic of atmospheric flow patterns, namely, the strong zonal flows and large-scale moving planetary waves. The oceans appear to exhibit a different class of solutions: large-scale steady geostrophic meridional flows in central oceanic regions, coupled, on account of the necessity for mass conservation, to narrow boundary-layer currents along the continental barriers on the western sides of the oceans.

To illustrate these two different classes, I have sketched examples as shown in Figure 1. On the left, we see the typical atmospheric flow pattern—a non-linear combination of zonal motion and planetary waves. Both of these geostrophic planetary motions were known separately by tidal theorists in the last century, but Rossby first recognized them in the atmosphere, introduced the β -plane in place of the sphere, and constructed a non-linear combination in which the planetary waves are carried round the earth by a basic zonal flow.

On the right are examples of the class of forced motion which exists with

meridional barriers. The chief feature is steady geostrophic flow in central portions of the ocean, and narrow inertial or viscous boundary layers on the western coasts to conserve mass. The latitudinal dependence of the pattern depends upon the latitudinal form of the forcing function. A wide variety of free solutions is also possible.



FIG. 1

The wind-driven ocean-current theories of Sverdrup, Munk, and myself are particular examples of the class of solutions with meridional walls. Dealing only with vertically integrated velocities, these theories avoid the necessity of dealing in detail with vertical shearing stresses; they suggest *a posteriori* that lateral shearing stresses are negligible in central oceanic areas. Thus, although they include applied surface stresses, these theories treat the central ocean in the framework of a frictionless model. At first, it was supposed that all the lateral friction was contained in the narrow western boundary-layer currents. Munk and Carrier treated the Kuroshio as a viscous boundary layer. Two years ago, Fofonoff discovered classes of steady frictionless circulations on the β -plane with meridional barriers. Last year, I found, from an analysis of some of Worthington's detailed cross-sections of the Gulf Stream, that potential vorticity is conserved in the Stream. This fact suggested the boundary-layer currents might be inertial rather than frictional. Quite recently, Charney has been able to construct a numerical example that looks so much like the real thing that it seems likely that these boundary-layer currents are probably inertial in character. He has applied this theory to the growth region of the Gulf Stream (from the Florida Straits to Cape Hatteras). We have thus advanced to the point where we regard the dynamical role of large-scale lateral frictional processes as limited entirely to the relatively small areas of breakdown (through meanders and eddies) of the inertial boundary-layer currents. However, the vertically integrated wind-driven ocean-circulation model is only a first step. The thermohaline circulation in the ocean appears to be a kind of internal mode of motion, whose vertically integrated transports vanish everywhere. My most recent study of observational material suggests that there are also western boundary-layer currents associated with these internal thermohaline modes. Indeed, in the deeper regions of the ocean, there is reason to believe that large-scale regions of sinking water masses and rising water masses are connected through narrow inertial currents.

In Figure 2 are presented the results of an analysis of actual hydrographic data in the Atlantic Ocean. I should warn you that many subjective elements enter this first crude schematic analysis. On the left are shown the transport lines

for the upper half of the ocean. Each line represents a flow of about 10 million cubic meters per second. On the right is the flow in the bottom half. As I see it, there is an internal mode of circulation, asymmetrical with the equator, connecting sinking regions in the North Atlantic with rising regions in the South Atlantic, crossing the equator in the form of an inertial boundary layer. The

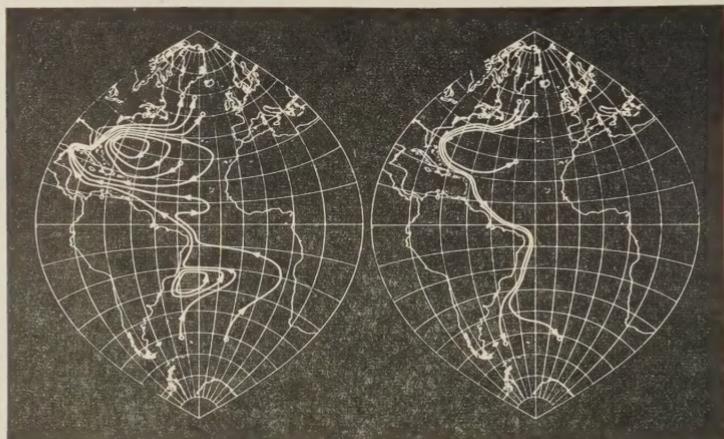


FIG. 2

lower half of this great cell is shown at the right. The upper half of this internal flow to the northward is superposed upon the wind-driven circulation. Thus, the total circulation of the upper layer is asymmetrical with respect to the equator even though the wind-driven part is nearly symmetrical. If we add these transports, that is, form a vertically integrated transport over the entire depth, a circulation pattern much more symmetrical to the equator, and quantitatively related to the wind stress alone, results.

If it is possible to restrict the dynamical role of vertical shearing stresses to the top few hundred meters, we can go quite far in our analysis of the flow in central oceanic regions. Steady meridional components of deep geostrophic flow must be accompanied at each level by horizontal mass divergence. Thus, vertical distribution of the vertical gradient of vertical velocity is known as a function of the depth of no meridional motion, itself undetermined from observation. But the vertical velocity must vanish at the bottom, and must also match the vertical velocity just beneath the surface wind-driven frictional layer. For a particular oceanic area, this completely defines the depth of no meridional motion, and the vertical velocity. In the Sargasso Sea, the only region where sufficient data are available, to make actual numerical calculations, I find downward motions above the main thermocline, opposed by upward motions of as much as 30 meters a year below the main thermocline, a field of vertical motion consistent with the existence in this region of abrupt temperature change with depth. In forming the simple wind-driven theory of oceanic circulation, the response of the ocean does not affect the field of applied wind stress. In the formulation of the thermohaline

circulation, it is not so certain that the heating function can be applied independently of the interdependence of the thermal fields of both the sea and air.

This brief review of the present theoretical status of the general oceanic circulation shows that the only portions of dynamical oceanography that we can make much of are those in which we can either sidestep internal friction altogether, or isolate it in a particular part of the problem which we do not discuss in detail, or, at worst, treat it parametrically. We do not meet internal friction head on. But the absence of internal friction in the theoretical formulations of models of the ocean and atmosphere and perhaps other geophysical studies does not mean that it is unimportant, rather, that our lack of understanding of turbulence on the geophysical scale is a formidable obstacle common to these branches of earth science. I offer this as an example of how our fields are united perhaps more by certain areas of common ignorance, rather than through those particular aspects already partially explored.

C. ECKART, *Scripps Institution of Oceanography, La Jolla, California: The generalized laws of geophysics.** C. Eckart stressed the need for generalized treatment of geophysical problems. He stated that generalized treatments were attempted near the beginning of the nineteenth century by men like Laplace. The present was a good time to initiate fresh attempts at generalized treatments.

J. G. CHARNEY, *Institute for Advanced Study, Princeton, New Jersey: Some basic problems in dynamic meteorology.* Two problems that have occupied the major attention of dynamic meteorologists in recent years have been the explanation of (a) the generation and motion of the great migratory cyclonic and anticyclonic vortices of middle latitudes, and (b) the mechanism by which the mean zonally averaged circulation of the atmosphere is maintained against frictional dissipation. The two were at first studied independently, but it has now come to be realized that they are interrelated. In the following, a brief historical description will be given of some of the principal investigations.

The theory of cyclones. The individual traveling disturbances occur on a scale much smaller than that of the solar heating, and under such circumstances it is natural to look for a hydrodynamical instability as the explanation of their origin. The first intimation of such a possibility occurs in the writings of Helmholtz (1888) who dealt with atmospheric motions at a surface of discontinuity separating air masses moving with different velocities. The idea was again taken up by V. Bjerknes (1916), who proposed to investigate all possible types of wave motions occurring in a compressible atmosphere on a rotating earth in the hope that among these would be found unstable motions resembling the observed cyclones of middle latitudes. An additional impetus for this program was supplied by the discovery of the polar front as a material surface of separation between warm and cold air masses by J. Bjerknes (1919) and the wave cyclone by J. Bjerknes and H. Solberg (1922). The mathematical investigation of the polar front instability was carried farthest by Solberg (1928) and Kotschin (1932). They succeeded in demonstrating

*Abstract not supplied by author, but furnished from notes taken during the conference.

that disturbances will form which bear some resemblance to the observed wave cyclones, but the models were too highly simplified to permit any conclusive verification of their theories. Other types of hydrodynamical instability were proposed, that of Rayleigh (1880) which occurs in the two-dimensional parallel flow of a fluid when the cross-stream velocity profile has a point of inflection and where the energy of the disturbance derives from the kinetic energy of the basic flow, and the instability discovered by Helmholtz (*loc. cit.*) which occurs for axially symmetric adiabatic displacements of a circular vortex when the angular momentum of the basic flow increases outward along isentropic surfaces. The latter was proposed by Raethjen (1941), Kleinschmidt (1941), and others, and the former by H. L. Kuo (1949). Again, because of the oversimplifications in the models and because of mathematical difficulties, it was virtually impossible to compare the results with actual atmospheric conditions.

With the increase in our empirical knowledge, it became possible to construct more realistic models of the atmospheric flows. J. Bjerknes (1937) recognized the importance of the tilted upper wave in the westerlies as a physical entity and by semi-empirical reasoning gave an explanation for its motion. A more general explanation was later given by C. G. Rossby (1939) on the basis of the Helmholtz vorticity theorem. Both writers demonstrated the importance for the motion of large-scale atmospheric systems of the geographical variation of the vertical component of the earth's vorticity, an effect which tends to produce cyclonic vorticity in southward-moving air masses and anticyclonic vorticity in northward-moving masses. This effect has been shown by H. Stommel (1948) to account for the westward intensification of the wind-driven ocean circulation.

The extension of the upper air network of observations revealed the frontal wave cyclone as but the surface manifestation of the upper wave. It then became reasonable to look for the energy of the unstable wave perturbation in the potential energy supply associated with the continuous horizontal temperature variations in the upper air. It was found (Charney 1947 and Eady 1949) that a zonal flow with a sufficiently large north-south temperature gradient and consequent large vertical shear would be unstable for wave perturbations in which the slopes of the particle trajectories were less than those of the isentropic surfaces. Perturbations of this type were found to correspond to the observed upper wave in both mass and velocity structure. The instability thus found was a direct generalization of gravitational instability to the case of a revolving stratified fluid, and was called "baroclinic" instability. It was of added significance that in order to overcome the quite considerable mathematical difficulties involved in the development of the theory a physical characterization was given for the difference between the large-scale meteorologically significant "planetary" motions of the atmosphere and the small-scale "noise" motions. A more complete theory was later developed by Charney (1948, 1955), Eliassen (1949), and Fjörtoft (1955). The characterization was based on the fact that the planetary motions are neither elastic oscillations nor oscillations in the gravitational or centrifugal force field of the rotating earth, but rather are of such a nature that there exists at all times a kind of equilibrium of forces, analogous to that which obtains in the equilibrium theory of the tides, in which there is a balance among the Coriolis and field accelerations and

the pressure field that does not involve the time. To a first approximation, the balance is expressed by the familiar geostrophic relationship. More generally, the balance condition may be derived from the property of horizontal quasi-incompressibility. Mathematically, it is possible to incorporate the balance condition into the equations of motion to derive a self-consistent set of equations which in effect "filter out" the insignificant sound and gravitational oscillations.

The formalism so created has been applied to the numerical integration of the equations of motion for atmospheric flows with the aid of large-scale, high-speed electronic computing machines. Between 1946 and 1952, one of the first of such machines was constructed at the Institute for Advanced Study under the direction of J. von Neumann and was thereafter used largely for meteorological purposes. Following its completion, a series of numerical integrations of the "filtering" equations were performed for a set of simplified mathematical models of the atmosphere involving a finite but varying number of degrees of freedom along each vertical. At length, a model was developed which led to successful predictions of cyclogenesis for actual weather situations (Charney 1954). The theoretical interest of this result lay in the fact that the model permitted only "baroclinic" instability and was free of external energy sources; thus, it was demonstrated that baroclinic instability is the primary cause of cyclogenesis.

The mean zonal circulation. The instability theories, insofar as they apply at all, presuppose the existence of a uniform zonal current upon which the traveling disturbance is superimposed. The explanation of this zonal current, which appears as a westerly wind extending to above the tropopause in middle latitudes and shallower easterly winds in polar and equatorial regions, is a necessary first step in any attempt to account theoretically for the climate of the earth—not to speak of climatic variation. The earliest theories were based on the idea that the mean circulation is an axially symmetric convective circulation, in which the heated air near the equator rises, moves toward the pole, where it loses its energy back to space, descends near the poles and moves equatorward at the ground. As was first pointed out by Hadley (1735), this type of motion when started from rest does, in its initial stage, give rise to the easterly trades in low latitudes, but it cannot persist as a steady circulation. Various later attempts which continued to presuppose an axially symmetric circulation likewise failed to account for the observed patterns of flow, and finally in 1926 H. Jeffreys showed that it was very likely that the transfer of heat and momentum by the asymmetric eddy motions are essential factors in the maintenance of the mean circulation. By an extensive analysis of wind and pressure observations, V. Starr (1954), J. Bjerknes (1955), and their collaborators were able to show that the eddy transfer mechanism is everywhere important and in some regions is dominant in the transfer of heat and momentum.

In an attempt to explain the linkage between the individual eddy element and the zonal circulation, Charney (1951) showed that the unstable disturbances, which form in the mid-latitude westerlies as unstable waves, derive their energy from the potential energy of the mean flow, but at the same time act as eddy agents in transferring part of their kinetic energy back into the kinetic energy of the mean flow, and thus compensate for the kinetic energy destroyed by friction.

Concomitantly, they transfer angular momentum from the low and high latitude easterlies, where it is *added* to the atmosphere by frictional torques to the mid-latitude westerlies, where it is *removed* by frictional torques acting in the opposite sense. This type of transfer occurs because the baroclinically unstable disturbance is *stable* in the two-dimensional Rayleigh-Kuo sense, that is, in the sense that the mean flow gains kinetic energy from the perturbation.

Eliassen (1952) and Fjörtoft (1951) developed the idea that the meridional component of the circulation is determined by the requirement that the Coriolis force associated with the zonal velocity component must be balanced by the zonally averaged horizontal pressure force, and that any unbalance created by large- or small-scale eddy frictional torques or by large- or small-scale eddy transfer of heat must instantaneously manifest itself as a forced meridional circulation tending to restore the balance. This requirement follows immediately from the balance relationship embodied in the filtering equations.

In 1955, N. Phillips actually was able to show by a numerical experiment that the above-mentioned processes do, indeed, combine to produce a mean flow very much resembling the mean flow in the atmosphere. He constructed a mathematical model of the atmosphere, heated at low latitudes and cooled at high latitudes, and subjected to ground friction. Starting with the atmosphere at rest, he integrated the equations of motion numerically to obtain a prediction for several months. Initially, a purely zonal flow developed in conjunction with the growth of a north-south temperature gradient. Then, as the temperature gradient increased in intensity, a perturbation with wave length given by the baroclinic instability theory began to amplify and at the same time to act as a turbulent eddy in transferring its kinetic energy into the energy of the mean westerly flow. Westerly winds increasing with height were created at middle latitudes, and easterly surface winds developed in the extreme high and low latitudes. Thus, the model exhibited both the typical phenomenon of cyclogenesis and the mechanism for transfer of energy into the westerlies. The flow, 30 days after the asymmetric perturbation had begun to amplify, bore a marked resemblance to the mean flow of the atmosphere, and the eddies which formed looked very like those that one observed in the atmosphere. The integrations also showed that a three-celled meridional circulation must exist in each hemisphere, with a thermally direct circulation in equatorial and polar regions and an indirect circulation in middle latitudes. The eddy gain of momentum by the upper atmosphere at middle latitudes is thus partially compensated by the action of the Coriolis force on the meridional circulations.

The picture one has of the atmosphere is that of a heat engine, which converts solar energy in the form of potential energy associated with horizontal temperature gradients into mechanical energy, which is dissipated into heat by friction. Most of the solar energy is reradiated into space at the same temperature at which it is absorbed and so does not participate in the thermodynamical process. Wulf and Davis (1952) found that the rate of decrease of entropy due to radiative processes and the rate of increase due to frictional dissipation come close to balancing and, consequently, that the atmospheric engine operates at near maximum efficiency. A measure of the potential energy available for conversion into mechanical energy by adiabatic processes has been defined by Lorenz (1955) in terms of the variance

of temperature. He finds for a simple model that the observed mean temperature field is very nearly that which corresponds to a maximum rate of increase of available energy and therefore to a maximum dissipation of mechanical energy. Such a principle, if it is found to hold generally, would be of immense value in the study of the general circulation.

A next step will certainly be to extend Phillips' calculations to models containing more realistic energy sources and sinks and topographical inhomogeneities, in an attempt to explain some of the asymmetries in the mean circulation. It is clear by now that in the electronic computing machine we possess a most powerful weapon for attacking a great number of geophysical problems that have hitherto resisted solution because of their mathematical difficulties.

References

- Bjerknes, J. (1919); On the structure of moving cyclones, *Geophys. Pub.*, **1**, No. 2, 8 pp.
 — (1937); *Theorie der aussertropischen Zyklonenbildung*, *Met. Zs.*, **54**, 462–466.
 — (1955); Investigations of the general circulation of the atmosphere, Final Report, General Circulation Project No. AF 19(122)–48 with Geophysics Research Directorate, U.S. Air Force.
 — and H. Solberg (1922); Life cycle of cyclones and the polar front theory of atmospheric circulation, *Geophys. Pub.*, **3**, No. 1, 18 pp.
 Bjerknes V. (1916); *Wellenbewegungen in kompressiblen schweren Flüssigkeiten*, Leipzig, Abh. Ges. Wiss., Phys.-Math. Kl.
 Charney, J. G. (1947); The dynamics of long waves in a baroclinic westerly current, *J. Met.*, **4**, 135–162.
 — (1948); On the scale of atmospheric motions, *Geophys. Pub.*, **17**, No. 2, 17 pp.
 — (1951); On baroclinic instability and the maintenance of the kinetic energy of the westerlies, C. R. Assemblée de Bruxelles, août-sept. 1951, Union Géod. Géophys. Internat., Assoc. Mét., *Symposium sur la circulation générale des océans et de l'atmosphère*, pp. 47–63.
 — (1954); Numerical prediction of cyclogenesis, *Proc. Nat. Acad. Sci.*, **40**, 99–110.
 — (1955); Generation of ocean currents by wind, *J. Marine Res.*, **14**, No. 4 (to be published).
 Eady, E. T. (1949); Long waves and cyclone waves, *Tellus*, **1**, 32–52.
 Eliassen, A. (1949); The quasi-static equations of motion with pressure as independent variable, *Geophys. Pub.*, **17**, No. 3, 44 pp.
 — (1952); Slow thermally or frictionally controlled meridional circulations in a circular vortex, *Astroph. Norvegica*, **5**, pp. 19–60.
 Fjörtoft, R. (1951); Stability properties of large-scale atmospheric disturbances, Compendium of meteorology, American Meteorological Society, Waverly Press, Inc., Baltimore.
 — (1955); On the use of space smoothing in physical weather forecasting, *Tellus*, **7**, 462–480.
 Hadley, G. (1735); Concerning the causes of the general trade winds, *Phil. Trans. R. Soc. (London)*, **39**, p. 58.
 Helmholtz, H. von (1888); On atmospheric movements, Berlin, *SitzBer. R. Prussian Acad. Sci.*, pp. 647–663.
 Jeffreys, H. (1926); On the dynamics of geostrophic winds, *Q. J. R. Met. Soc.*, **52**, pp. 85–101.
 Kleinschmidt, E. (1941); Stabilitätstheorie des geostrophischen Windfeldes, *Ann. Hydrogr.*, **10**.
 Kotschin, N. (1932); Über die Stabilität von Margulesschen Diskontinuitätsflächen, *Beitr. Physik frei Atmos.*, **18**, pp. 129–164.
 Kuo, H. L. (1949); Dynamic instability of two-dimensional non-divergent flow in a barotropic atmosphere, *J. Met.*, **6**, pp. 105–122.
 Lorenz, E. N. (1955); Available potential energy and the maintenance of the general circulation, *Tellus*, **7**, pp. 157–167.

- Phillips, N. A. (1955); The general circulation of the atmosphere, a numerical experiment (in press).
- Raethjen, P. (1941); Labile Gleitumlagerungen, Ann Hydrogr., 10.
- Rayleigh, Lord (1880); On the stability, or instability, of certain fluid motions, Scientific Papers, Cambridge, University Press, 1, pp. 474-487.
- Rossby, C. G. (1939); Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action, J. Marine Res., 2, 38-55.
- Solberg, H. (1928); Integrationen der atmosphärischen Störungsgleichungen, Geof. Pub., 5, No. 9.
- Starr, V. P. (1954); Studies of the atmospheric general circulation. Final Report, General Circulation Project No. 19(122)-53 with Geophysics Research Directorate, U.S. Air Force.
- Stommel, H. (1948); The westward intensification of wind-driven ocean currents, Trans. Amer. Geophys. Union, 29, 202-206.
- Wulf, O. R. and L. Davis (1952); On the efficiency of the engine driving the atmospheric circulation, J. Met., 9, 79-82.

DAVE FULTZ, *University of Chicago, Chicago, Illinois: A fluid convection experiment of special theoretical interest.** Since 1947, in work at the University of Chicago and elsewhere, it has become clear that a variety of large-scale geophysical phenomena, especially in meteorology and oceanography, can be studied in quantitative model experiments that were previously regarded as unattainable. An important class of these experiments deals with motions of a cylindrical body of fluid driven by axially symmetric heat and cold sources, roughly as in the earth's atmosphere (Fultz 1951, Starr and Long, 1953). When the fluid is contained in the annulus between two concentric cylinders rotated about their common vertical axis with the inner wall cooled and the outer wall heated, Hide (1953 and 1956, Fultz 1952) found that certain very regular wave motions could be generated. Figure 1 illustrates a case of this kind at a wave number of 5. The band of aluminum powder on the top surface outlines the undulations of a westerly (counter-clockwise) jet current, the waves on which are propagating without change of shape slowly toward the east, just as do their atmospheric counterparts. Theories for some of the phenomena, which at least in broad outline are successful, have been given, notably by Kuo (1955), using a type of analysis very similar to that which has been applied by many authors to problems of the onset of Rayleigh-Benard type cellular convection. In the present note, a class of time-variations to which these wave motions can be subject will be discussed. These time-variations were first discovered and named "vacillation" by Hide (1956, Runcorn 1954).

Vacillation consists of a more or less regular periodic sequence of alterations in the wave train and its associated physical effects. Figures 2 and 3 illustrate two stages in the field of motion at the top surface during a five-wave vacillation, with outer heat source and inner cold source. In Figure 2, the waves are comparatively weak in amplitude, have open troughs, and tilt back toward the southwest. In the course of their propagation, the waves now swing forward until the trough lines are almost radial or even tilt southeastward. Simultaneously, they

*The research here reported was made possible through support extended by the Geophysics Research Directorate, Air Force Cambridge Research Center, under Contract AF 19(604)-1292.



FIG. 1—Instantaneous flash photograph (130555-1-2) of a steadily propagating train of five waves on a westerly (counter-clockwise) jet at the top surface of water in a cylindrical annulus. The aluminum powder on the top spontaneously collects along the jet and in the anticyclonic circulations in the ridges.

Experimental conditions: Water plus 0.5 gm/liter Lakeseal detergent, depth 13.0 cm, inner radius 2.48 cm, outer radius 4.95 cm, rotation 2.50 sec^{-1} counter-clockwise, C_E 12.4 cm/sec, rim hot, mean radial temperature difference over 2.4 cm 1.9°C , mean vertical temperature difference over 9.2 cm 1.8°C , mean temperature 20.6°C , outer bath 22.9°C , inner bath 19.0°C , wave propagation rate 0.003 rev toward east per pan revolution.

begin intensifying and soon form strong closed cyclonic vortices at the top. Figure 3 shows this phase just before the cyclones reach maximum intensity.

The cyclones then begin to change shape and go eventually into open, large-amplitude troughs with strong southwest tilts. Gradual weakening of the waves then returns the train to the phase of Figure 2, and the whole process repeats. The longitudinally averaged zonal velocities accompanying the cycle as measured from streak photographs are shown in Figure 4. The relative velocities are measured non-dimensionally as fractions of C_E , the absolute speed of a fixed point at maximum radius. The values obtained are in the same numerical range as observed atmospheric values, and the time-section shows that in the vacillation cycle the average zonal wind profile alternates between having the principal westerly wind maximum near the inner wall and near the outer wall. At the same time, the over-all average zonal component undergoes a fluctuation in time with the same period over a range of the order of 30 to 50 per cent of its value. Obviously, many other properties of the wave train, such as the eddy momentum transports, must exhibit similar fluctuations. One of the most striking and characteristic of these latter properties is the heat transported from the heat source to the cold source by the wave train in the working fluid. Figure 5 gives the observed variation of heat transport for this case.

This and other types of vacillation are closely akin in at least qualitative and probably many quantitative properties to the atmospheric index cycle (Rossby, Willett 1948, Namias 1950). But the most intriguing aspect is the general range

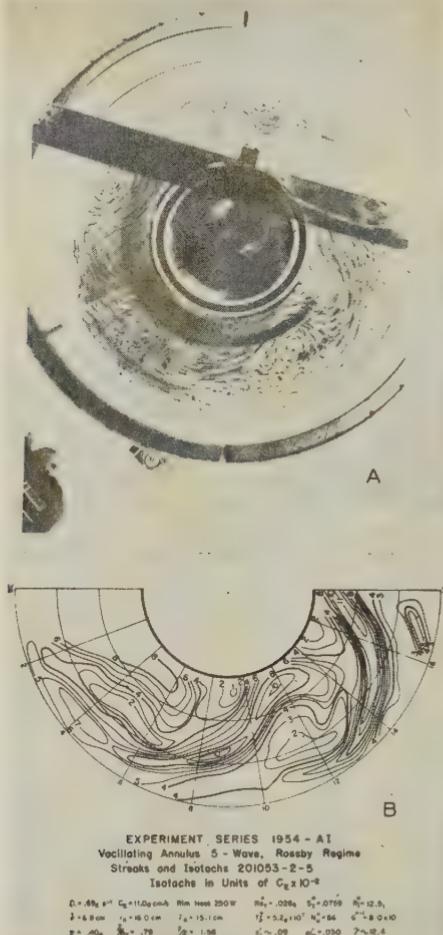


FIG. 2—Streak photograph (201053-2-5) and isotach analysis of a weak amplitude stage for a vacillating train of five waves driven by rim heating and center cooling. Velocities on the isotachs are in percentage of C_E and are in the relative (pan) coordinate system. Note the narrow elongated jet patterns, which reach values of 10 to 11 per cent.

Experimental conditions: Water plus 0.5 gm/liter Lakeseal detergent, depth 6.8 cm, inner radius 6.5 cm, rim radius at water level 16.0 cm, water volume 4,000 ml, rotation 0.692 sec counter-clockwise, C_E 11.1 cm/sec, over-all mean radial temperature difference over 7 cm 1.6°C, over-all mean vertical temperature difference over 5 cm 4.4°C, mean temperature 25.8°C, average wave propagation rate 0.030 rev per pan revolution toward east, exposure time 1.02 sec.

of the time scale for the vacillation periods. In the case above, this period is just about 12 revolutions of the cylinder, with some variation from cycle to cycle. Now the velocity units used earlier and the most important non-dimensional similarity criteria for the experiment as a model of the atmosphere are such that the model time scaling requires simply that the time for one cylinder revolution

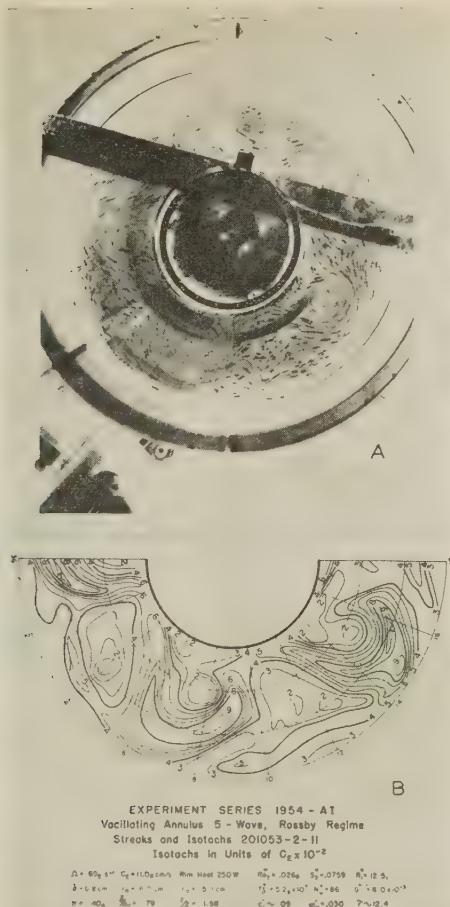


FIG. 3.—Streak photograph (201053-2-11) and isotach analysis approximately one-half cycle after Figure 2. Three of the waves have formed closed cyclonic vortices and the other two will do so shortly. Note the radical alteration in the isotach patterns.

Experimental conditions: As in Figure 2, except exposure time 1.00 sec.

correspond to one day (Fultz 1956). It is unlikely that this correspondence will be much modified by any future adjustments in the choice of optimum similarity conditions. A time of 12 "days" is of the order of those estimated as typical in the much less clear-cut situations where index cycles have been identified in the atmosphere. By varying experimental conditions, it is possible to vary the vacillation periods over a wide range, of which the longer ones are of the most interest in connection with our ignorance of long-term phenomena and their causes in the atmosphere.

Figure 6 gives an example of very well-defined periodicity in both the horizontal and vertical temperature differences measured at a fixed longitude (relative to

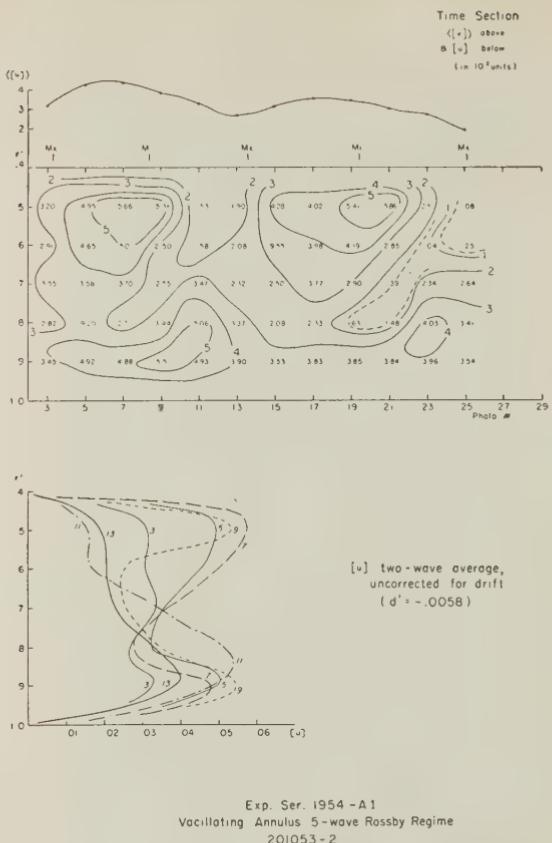


FIG. 4.—Time-section against radius and individual radial profiles of the zonal velocity component averaged with respect to longitude through two wavelengths. The photographs were taken at intervals of one revolution and photograph number therefore equals time in "days." The upper curve gives the variation of the radial average of these mean zonal speeds and, while it has a downward trend, clearly shows a fluctuation from high to low zonal speeds through the vacillation cycle. Speeds are in percentage of C_E . Mx and Mi denote the times of maximum and minimum heat transport, respectively, to the cold source.

Experimental conditions: As in Figure 2.

the cylinder of Fig. 1) by two thermocouples. The motion is at a wave number of 2, with very strong vacillation all the way to a stage of axially symmetric motion on the cycles toward the end of the records. Thus, here the wave number changes from 2 to 0 periodically during the vacillation (other more complicated changes are possible). The intensity of the motion increases with time (to the left) as the temperature gradients are raised. The length of the vacillation cycles also changes systematically to 160 "days" and more just before a purely axially symmetric motion becomes established. It is uncertain just how long similar periodicities can become, but less well-defined modulations superimposed on heat transport fluctua-

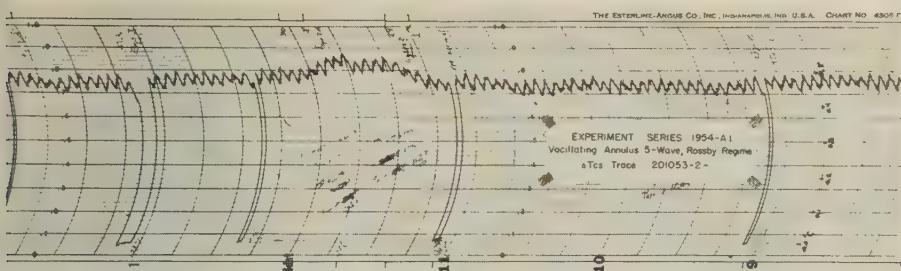


FIG. 5.—Trace proportional to the heat transport to the cold source in the 201053-2 experiment obtained from a thermocouple measuring the difference between the inflow and outflow temperatures of the water supply to the cold source. The cycle length is roughly 12 "days." The average heat transport value is about 12.7 g cal/sec, but this is uncorrected for extraneous heat supplies to the source, which may be fairly large.

Experimental conditions: As in Figure 2.

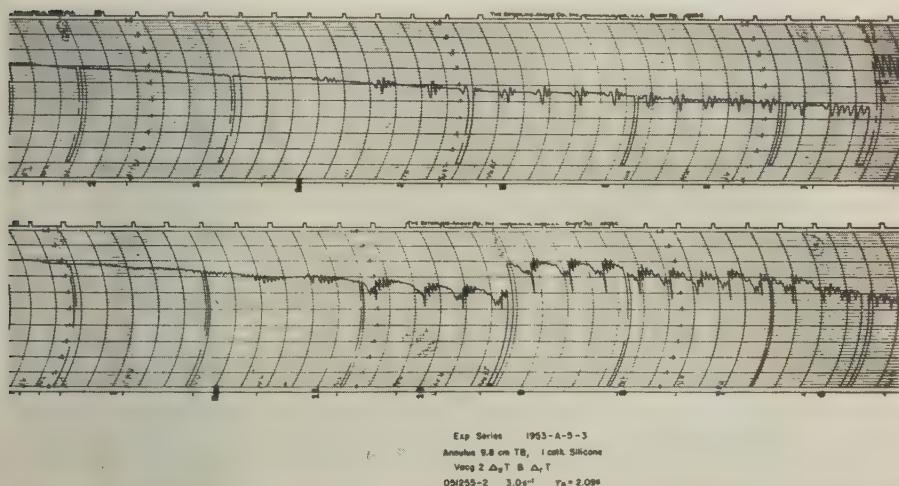


FIG. 6.—Long-term periodic variations in the horizontal (below) and vertical (above) temperature differences observed at a fixed longitude in the small annulus of Figure 1. Vacillation from two waves to symmetric motion is occurring. Time increases to the left. The temperature gradients are being gradually increased and the length of the vacillation cycle gradually increases, finally reaching more than 160 "days." The periodicity even in details is very striking.

Experimental conditions: One centistoke Dow-Corning silicone, geometry as in Figure 1, rotation 3.00 sec^{-1} , rim hot, mean radial temperature difference over 2.4 cm 3.7° rising to 4.7°C , mean vertical temperature difference over 9.2 cm 4.0° rising to 6.5°C , mean temperature 32.2°C , outer bath 34.3° to 34.8°C , inner bath 28.4° to 25.2°C .

tions such as in Figure 5 have already been observed with rough periods in the range 1,000 to 2,000 "days."

Theories for vacillation have not yet been found, but it is not unlikely that when they are they will be found to have some relation to the phenomena of overstability predicted and observed in certain cases of rotating Benard cellular

convection due to vertical instability (Chandrasekhar and Elbert 1955, Fultz and Nakagawa 1955). The phenomena are clearly of the highest interest, because there is very little doubt that they are due primarily to internal mechanisms (the heating and cooling baths being maintained substantially constant) and are thus relevant to questions of external (such as solar) *vs* internal causes for the cognate atmospheric occurrences. Also, quite generally, their clearly defined character and the ability to impose the experimental conditions at will make them eminent subjects of theoretical study in the attempt to understand the much more complicated and less well-defined behavior of the atmosphere and other geophysical prototypes.

References

- Chandrasekhar, S., and D. D. Elbert (1955); The instability of a layer of fluid heated below and subject to Coriolis forces—II, Proc. R. Soc., A, **231**, 198–210.
- Fultz, D. (1951); Experimental analogies to atmospheric motions, Compendium of meteorology (edited by Thomas F. Malone), American Meteorological Society, pub. by Waverly Press, Inc., Baltimore, 1235–1248.
- Fultz, D. (1952); On the possibility of experimental models of the polar-front wave, J. Met., **6**, 379–384.
- Fultz, D. (1956); A survey of certain thermally and mechanically-driven fluid systems of meteorological interest, Proc. 1st Symposium Geophys. Models, Baltimore, September 1953.
- Fultz, D., and Y. Nakagawa (1955); Experiments on over-stable thermal convection in mercury, Proc. R. Soc., A, **231**, 211–225.
- Hide, R. (1953); Some experiments on thermal convection in a rotating liquid, Q. J. R. Met. Soc., **79**, 161.
- Hide, R. (1956); Geomagnetism: Fluid motion in the earth's core and some experiments of thermal convection in a rotating liquid, Proc. 1st Symposium Geophys. Models, Baltimore, September 1953.
- Kuo, H. L. (1955); On convective instability of a rotating fluid with a horizontal temperature contrast, J. Marine Res., **14**, 14–32.
- Namias, J. (1950); The index cycle and its role in the general circulation, J. Met., **7**, 130–139.
- Rossby, C. G., and H. C. Willett (1948); The circulation of the upper troposphere and lower stratosphere, Science, **108**, 643–652.
- Runcorn, S. K. (1954); The earth's core, Trans. Amer. Geophys. Union, **35**, 49–63.
- Starr, V. P., and R. R. Long (1953); The flux of angular momentum in rotating model experiments, Geophysical Research Paper No. 24, 103–113.

VICTOR P. STARR, *Massachusetts Institute of Technology, Cambridge, Massachusetts: Modern developments in the study of the general circulation of the atmosphere.* The purpose of this discussion is to present a general account of the research program concerning the study of the global circulation of the atmosphere, pursued during the past few years by my colleagues and myself at the Massachusetts Institute of Technology. In a space as brief as is now at my disposal, it is possible to give only a short sketch of this work, the most fundamental aim of which has been to discover the mode of operation of the atmosphere as a heat engine.

The source of energy for all atmospheric motions resides in the heating by solar radiation, all other energy sources being quite minor. Furthermore, the action of solar radiation depends upon the fact that it provides a differential

heating between more polar and more equatorial latitudes in each hemisphere. Uniform heating of the atmosphere would, of course, not result in the differences in pressure along horizontal surfaces which are necessary for the creation of kinetic energy (see, for example, Starr 1948). In fluid mechanics, it is customary to refer to the process of generation of motion by differential heating as convection. It is therefore, a process of convection, which one must study in attempting to understand the workings of the general circulation.

In these attempts, it is convenient to make reference to the classic investigations of M. Margules, early in this century. Margules (1903) pointed out that in a closed atmospheric system generation of kinetic energy takes place in proportion to the disappearance or release of potential energy and internal heat energy. Owing to the fact that in an air column extending upwards in an unlimited fashion and in hydrostatic equilibrium the latter form of energy is proportional to the potential energy, it therefore suffices for reason of brevity to speak only of potential energy. The researches of Margules also pointed out that the release of potential energy is accomplished by the rising of warm air and sinking of colder air, which, in a closed system, would represent a sinking of the center of gravity.

In the actual atmosphere, the radiational heating continuously replenishes the supply of available potential energy (see Lorenz, 1955), while the process of transformation into kinetic energy proceeds as outlined by Margules at some average rate sufficient to overcome frictional losses. In these terms, we may now state that one of the most fundamental questions which general circulation studies must include is the specification of the components of motion in the atmosphere which are actually responsible for the releasing of potential energy. Various other weighty and important questions also arise, of course, but this one may be looked upon as a starting point. Thus, another question relates to the manner in which the kinetic energy of the zonally-averaged motions is maintained, since although these motions are known to be present they are not an immediate consequence of the convective process. Logically then, there must exist a connecting link whereby the kinetic energy generated by the convection process becomes in part funneled into these components of motion.

In order to try to arrive at suitable answers to these and many other related questions, our program of general circulation research at M.I.T. has involved three more or less distinct approaches. The first and perhaps most important branch of our work has been an extremely extensive study of meteorological atmospheric data for the northern hemisphere. The second approach has been through the study of model experiments, which in recent years, thanks to the work of Prof. Fultz at the University of Chicago, have yielded analogues to the hemispheric circulation of atmosphere. In the third place, we have pursued extensive theoretical analyses, both from the standpoint of securing analytical solutions and also more recently through the application of high-speed digital computers. It is my intention to give a bare thumb-nail sketch of the results obtained in each of these lines of endeavour.

In the past, as mentioned by Dr. Charney, the basic convective motions in the atmosphere have been looked upon as being a general rising of air at lower latitudes and sinking at higher latitudes in the form of toroidal overturnings,

similar to those involved in Hadley's (1735) theory of the trade winds, published shortly after the time of Newton. A number of variations of this scheme were put forth during the course of time up to the present (for example, Ferrel 1885, Oberbeck 1888). All, however, ascribe the motions of the general circulation as being due to the release of potential energy by this type of overturning process (Rossby, 1947, is an exception). Any verification of these theories from direct observations is dependent upon the accumulation and reduction of a vast amount of data. This was actually one of the primary objectives of our observational studies. The results are that the sum total effect of toroidal overturnings as measured from the data for the northern hemisphere is, if anything, in such a direction as to convert kinetic energy back into potential energy (Starr 1954). This arises from the indication that the most vigorous toroidal overturning observable is a reverse one in middle latitudes, involving descent of warm air to the south and ascent of cold air to the north.

In view of this situation, it follows that there must be other fundamental convective motions in the atmosphere which liberate potential energy and convert it into kinetic energy. What are then the observational indications for this alternative process? The results show that the convection proceeds in terms of many smaller cells, these in fact being the cyclones and anticyclones of middle latitudes which involve the rising of warm air masses and sinking of cold ones (White and Saltzman, 1956). It would thus appear that purely from measurements of atmospheric motions in relation to air temperature the atmosphere shuns extremely large convective cell sizes.

Speaking now of experimental studies, it is manifestly true that laboratory models which duplicate hemispheric conditions of the atmosphere in all detail are impossible. However, if one sets one's sights merely upon the reproduction of the largest scale phenomena and more specifically upon those processes involved in these phenomena which turn out to be relatively insensible to the presence of details, success may be achieved, as has been so well demonstrated by the studies of Prof. Fultz. The particular experiments which we have studied are those in which motions relative to a rotating cylindrical vessel are generated in water, purely as a consequence of heating the (plane) bottom at the rim and cooling nearer the center. A variety of regimes may be obtained in such experiments as a result of changes principally in the intensity of differential heating and rate of rotation. Under proper conditions, flow patterns are obtained bearing an unmistakable resemblance to those found in the hemispheric circulation in the atmosphere (for example, Fultz and Corn 1954, Hide 1953). This resemblance is not confined to one level, but exhibits similarity in vertical structure as well, reproducing such features as occluding cyclones and fronts near the bottom in proper relation to the cyclonic and anticyclonic troughs and ridges at higher levels (Faller, 1956).

The so-to-speak meteorological regime is distinguished from a regime of symmetrical convection which occurs at a sufficiently slower rate of rotation (or stronger heating with the same rotation). These axially-symmetrical motions are characterized by a radial inflow of the fluid near the top and a divergence near the bottom, which results from the ascent of the fluid over the heat source and a

sinking above the cold source at the center. This regime, therefore, exemplifies the action presupposed in the classical theories of the general circulation. Significantly, however, it is not the regime which has meteorological similarity. The one discussed earlier, which has such similarity, is moreover characterized if anything by a radial outflow of fluid near the top over practically all radii, much as is found in the atmosphere over a wide range of latitudes.

In other experimental examples of convection, which need not be direct analogues of atmospheric processes, such as convective motions of the Bénard type, it is simple to demonstrate that one effect of the presence of rotation is to diminish the characteristic cell sizes in the plane normal to the axis of rotation. One may thus, for example, obtain Bénard convection cells a foot or two in vertical extent but only an inch or two in horizontal cross-section. It is useful to regard the convective motions in the cylindrical vessel described above as an extension of this action of rotation. In other words, we are again confronted by a preference of the fluid to resort to smaller convective cell sizes in the case of strong rotation, other things being unchanged.

Since the hemispheric air motion, and also the circulations in the experiment possessing meteorological similarity, are characterized by strongly developed zonal motions, one may ask how kinetic energy resulting from the convective overturnings becomes so organized. One superficially attractive feature of the classical theories for the general circulation is the simplicity with which this connecting mechanism is visualized. It is there supposed that the toroidal convection generates kinetic energy, which in the first instance appears as kinetic energy of meridional motions, but which immediately becomes converted to kinetic energy of mean zonal motions by an essentially quasistatic process, through the action of Coriolis forces (this presumably is the actual mechanism in the heated cylinder when the symmetrical regime is present). If, however, the toroidal circulations actually present in the atmosphere (or in the meteorological regime in the heated cylinder) operate to increase the potential energy at the expense of kinetic energy, this process cannot be used to maintain the mean zonal motions. From the physical equations of motion, it follows that only one other alternative mechanism of any significance can perform this function. The alternative mechanism involves the flow of kinetic energy from the larger scale non-zonal disturbances into the mean zonal flow (for example, Kuo, 1951). This is in direct opposition to the state of affairs in the case of turbulent phenomena, where the kinetic energy becomes degraded into smaller and smaller eddies. From the standpoint of direct measurements in the atmosphere, the process envisaged here involves a flow or transport of angular momentum from zones of low angular velocity about the polar axis into regions of high angular velocity (Starr, 1953). It is to be noted that the observational evidence which has by now been obtained for the presence of this action can scarcely be disputed (see also, for example, Starr and White 1954, Mintz 1951).

From the standpoint of philosophical considerations, one may with profit observe that the non-zonal disturbances in the atmosphere differ in an essential manner from the disturbances visualized in most turbulence studies. The former ones, as we have seen, are the seat for the release of potential energy which becomes

converted most directly into the kinetic energy of the disturbances. The system thus involves a systematic insertion of energy into one scale of eddies. One is therefore not confronted by any fundamental inconsistency, if some of this energy is then transferred systematically to maintain the mean motion. No doubt, other examples of fluid motion in which eddy kinetic energy is so transferred into the mean motion will be found in the future.

As might be supposed, the third branch of our work has consisted of efforts to deduce theoretically the essential nature of the general circulation, and also of its experimental analogues, as a consequence of the hydrodynamical equations. In the attempts to do this by analytical means, one may be guided by various theoretical studies of other instances of convection, such as the theoretical analysis of the Bénard problem by Rayleigh (1916), Jeffreys (1928), and others. More recently, the analyses of certain convective problems due to Chandrasekhar for astrophysical applications have been of great use to us. The procedures involved consist of the use of linearization and the determination of the modes of convection which have a positive and appreciable rate of development. As to the results, it is desirable at the outset to remark that in other instances of convection such as those studied by Chandrasekhar (1953) and others, the theoretical effect of the presence of rotation is to diminish the cell size of convection units, as was stated in connection with the experimental results. In the case of the atmosphere and also for the meteorological regime in the rotating experiments, this same theoretical result is obtained (Kuo 1954, 1955, 1956; Lorenz 1953). Thus, it is confirmed also theoretically that in a system such as the atmosphere convection cannot proceed in the form of large axially symmetrical toroidal components of motion, but rather is constrained by the rotation to break up into a number of smaller cells, which in actuality are the cyclonic and anticyclonic disturbances of middle latitudes.

Through the use of analytical techniques, it is also possible to investigate the conditions under which kinetic energy may be exchanged between the mean motion and the eddies. Such studies have much in common with classical stability studies discussed by Helmholtz (1868), Rayleigh (1913), Heisenberg (1924), Tollmien (1929), and more recently by Lin (1945), to name but a few. When a suitable arrangement of circumstances is made, the result is gained that disturbances having the character of cyclones and anticyclones in the atmosphere would transfer their kinetic energy into the mean zonal flow, thus underlining the results from observational studies and the inferences from the laboratory models (Kuo 1949, 1953).

As discussed by Dr. Charney, a numerical solution for the gross features of the general circulation has been obtained by Phillips (1955) at the Institute for Advanced Study, through the use of high-speed electronic computation. These results are in very good agreement with our observational and theoretical results as here presented, so that the desirability of very intensive further work along such lines is strongly suggested. Motivated by similar aims, several of my colleagues have for some time been engaged in the numerical integration of the equations for a two-layer model of the atmosphere in the northern hemisphere and also for a corresponding three-dimensional model. In order to eliminate possible sources of misconception, it may be well to point out that in such work the effects of radia-

tional heating and cooling are taken into account, as is also frictional dissipation. An answer is then sought from the equations as to the regime of motion which ultimately develops. At the present moment, it is still too early to predict the outcome of our own computations, although it is reasonable to suppose that results comparable in essence to those of Phillips will follow.

As a general conclusion, it would appear that meteorologists now have for the first time a correct framework for the discussion and further study of the mechanics of the general circulation. In the course of future years, this cannot help having a profound influence on almost every branch of the science. As an immediate prospect, it is to be hoped that numerical solutions will be designed which incorporate more and more detailed conditions, such as the effects of orography, land and sea contrasts, seasonal effects, and possibly various other variations in the incoming solar radiation, both real and hypothetical. One hardly needs to enumerate here the variety of scientific questions which would have light thrown upon them from such investigations.

References

- Chandrasekhar, S. (1953); The instability of a layer of fluid heated below and subject to Coriolis forces, *Proc. R. Soc., A*, **217**, 306–327.
- Faller, A. J. (1956); A demonstration of fronts and frontal waves in atmospheric models, *J. Met.*, **13** (in press).
- Ferrel, W. (1889); A popular treatise on the winds, New York, John Wiley and Sons, Inc.
- Fultz, D., and J. Corn (1954); Synoptic analysis of convection in a rotating cylinder, *Geophys. Res. Papers*, **34**, Geophysics Research Directorate, Cambridge, Mass.
- Hadley, G. (1735); Concerning the causes of the general trade winds, *Phil. Trans. R. Soc. (London)*, **39**, 58. (Reprinted in "The Mechanics of the Earth's Atmosphere" by C. Abbe, Smithsonian Misc. Coll., **51**, 1910.)
- Heisenberg, W. (1924); Über Stabilität und Turbulenz von Flüssigkeitsströmen, *Ann. Physik*, **4**, 74, 577–627.
- Helmholtz, H. von (1868); Über discontinuirliche Flüssigkeitsbewegungen, Berlin, Monatsber., 215–228. (Reprinted in "The Mechanics of the Earth's Atmosphere" by C. Abbe, Smithsonian Misc. Coll., **843**, 58–66, 1891.)
- Hide, R. (1953); Some experiments on thermal convection in a rotating liquid, *Q. J. R. Met. Soc.*, **79**, 161.
- Jeffreys, H. (1928); Some cases of instability in fluid motion, *Proc. R. Soc., A.*, **118**, 195–208.
- Kuo, H. L. (1949); Dynamic instability of two-dimensional nondivergent flow in a barotropic atmosphere, *J. Met.*, **6**, 105–122.
- (1951); A note on the kinetic energy balance of the zonal wind systems, *Tellus*, **3**, 205–207.
- (1953); On the production of mean zonal currents in the atmosphere by large disturbances, *Tellus*, **5**, 475–493.
- (1954); Symmetrical disturbances in a thin layer of fluid subject to a horizontal temperature gradient and rotation, *J. Met.*, **11**, 399–411.
- (1955); On convective instability of a rotating fluid with a horizontal temperature contrast, *J. Marine Res.*, **14**, 14–32.
- (1956); Energy releasing processes and stability of thermally driven motions in a rotating field, *J. Met.*, **13** (in press.)
- Lin, C. C. (1945); On the stability of two-dimensional parallel flows, *Q. Appl. Math.*, **3**, 117–142, 218–234.
- Lorenz, E. N. (1953); A proposed explanation for the existence of two regimes of flow in a rotating symmetrically-heated cylindrical vessel, Symposium on Model Experiments, Baltimore, September 1953.

- Lorenz, E. N. (1955); Available potential energy and the maintenance of the general circulation, *Tellus*, 7, 157-167.
- Margules, M. (1903); Über die Energie der Stürme. *Jahrb. Zentralanst. Meteor. Geodyn.*, Wien.
- Mintz, Y. (1951); The geostrophic poleward flux of angular momentum in the month of January, 1949, *Tellus*, 3, 195-200.
- Oberbeck, A. (1888); Über die Bewegungerscheinungen in der Atmosphäre, *SitzBer. Ak. Wiss.*, 383-395, 1129-1138. (Reprinted in "The Mechanics of the Earth's Atmosphere" by C. Abbe, *Smithsonian Misc. Coll.*, 843, 176-197, 1891.)
- Phillips, N. A. (1955); The general circulation of the atmosphere—a numerical experiment (in press).
- Rayleigh, Lord (1913); On the stability of the laminar motion of an inviscid fluid, *Phil. Mag.*, 26, 1001-1010.
- (1916); *Scientific Papers*, 6, Cambridge, University Press, 432-446.
- Rossby, C. G. (1947); On the distribution of angular velocity in gaseous envelopes under the influence of large-scale horizontal mixing processes, *Bull. Amer. Met. Soc.*, 28, 53-68.
- Starr, V. P. (1948); On the production of kinetic energy in the atmosphere, *J. Met.*, 5, 193-196.
- (1953); Note concerning the nature of the large-scale eddies in the atmosphere, *Tellus*, 5, 494-498.
- (1954); Commentaries concerning research on the general circulation, *Tellus*, 6, 268-272.
- and R. M. White (1954); Balance requirements of the general circulation, *Geophys. Res. Papers*, 35, Geophysics Research Directorate, Cambridge, Mass.
- Tollmien, W. (1929); Über die Entstehung der Turbelenz, I. Mitt., *Göttingen, Nachr. Ges. Wiss. (Nene Folge)*, 1, 20-44.
- White, R. M., and B. Saltzman (1956); On conversions between potential and kinetic energy in the atmosphere, *Tellus* (in press).

WALTER M. ELSASSER, *University of Utah, Salt Lake City, Utah*: **Background of the geomagnetic dynamo theory.** Those who have watched closely the development of the geophysical sciences during the last 10 to 20 years have witnessed a remarkable change in this field, on which the appearance of a spate of new journals in various countries is but one external sign. It is not just the emergence of a new set of personalities, normal accompaniment of the lapse of time, and not the general broadening of scientific activity to be equally observed elsewhere, but something more fundamental, a change in quality rather than purely in extension. By way of introduction to my subject, I should like to devote a few words to this phenomenon.

The philosopher Kant has emphasized in a famous passage that the scientist (and he is talking in particular of the physicist) does not just observe Nature; instead he asks questions of her under carefully chosen conditions *which he himself imposes*. This is the essential nature of experiment, and this is the way in which physics, or most of physics, has developed. It leads to the establishment of fundamental laws. The method has, of course, been immensely successful, and we need hardly enlarge on the progress in our understanding of the fundamentals of physics which has been achieved in even so short a span of time as the first half of our century.

But times have changed. Where once the leaning tower of Pisa or some pieces of hardware gathered in Ampère's garrett provided the facilities to establish a new fundamental law, we now often require an investment of hundreds of thousands if not millions of dollars in cyclotrons, linear accelerators, etc. This changing aspect of scientific technique is often foremost in the mind, not only of the educated

public, but also of a large fraction of the scientific community. But by being so prominently impressed upon us, it has tended to overshadow another aspect of scientific progress inextricably linked with our broader insight into the basic laws of physics.

The quantitative understanding of fundamental law is but one facet of scientific activity. It is, of course, not correct to confound the scientist with the experimentalist; very often the scientist is called upon to observe phenomena and then to explain them in terms of known fundamental laws. This could not be done very successfully during a period in which these laws themselves were only very partially known. The turning point was reached, it seems, with the advent of quantum mechanics some 30 years ago. Take, for an example, the change which this has brought about in crystallography, the physics of the solid state. In the "classical" period, it was necessary to determine empirical parameters of mysterious origin in order to describe the mechanical, electrical, or optical properties of a crystal. On the basis of quantum mechanics, we can, in principle, compute all these properties once the chemical composition is known. Needless to say, this is not the way actual investigation takes place. Detailed measurements are interlaced with mathematical analysis; one proceeds inductively rather than purely deductively, but this does not detract from the obvious intrusion of more and more analytical and deductive elements into a field where knowledge not so long ago was largely empirical.

While this advance went on in atomic and molecular physics, so-called classical physics has not stood still. The nineteenth century mathematical physicists studied primarily the dynamics of linear systems, a very special class, indeed. Poincaré, who flourished toward the end of the last century, is usually credited with the foundation of systematical non-linear mechanics. At about the same period, the investigation of turbulence became prominent. As a result of the progress growing from these endeavors, we now have a very much deeper understanding of the behavior of fluids, of deformable solids, and generally of matter in bulk.

It is a truism to say that Nature in the raw is complicated. The preceding remarks illustrate two outstanding types of complexity: chemical complexity as in crystalline solids, say minerals, and dynamical complexity as, say, in turbulent fluids. Often, of course, both supervene simultaneously, making the problems even more complex. It is still a far cry, of course, from these intricacies of inorganic nature to the formidable complexity of the living organism. Still, it seems that by now there has been reached a stage in the development of scientific methods where we need no longer despair of analyzing and understanding a considerable number of at least the inorganic natural phenomena as they appear to us, outside of the laboratory, *in their normal setting*.

Here, the "pure" scientist joins hand with the "applied" scientist. The latter also must frequently deal with rather complex systems, whether it be the properties of an intricate electronic device, the dynamics of high-speed propulsion, or the stability of materials in a nuclear reactor. Sometimes perhaps the physicist working on a jet engine is as close to an oceanographer as he is to the man who investigates the properties of mesons.

Recent scientific techniques, in particular electronic techniques, are of immense

importance in the study of complex systems. Electronic techniques enter in three successive stages of such an effort. First, they permit the very rapid taking of large bodies of data and their instantaneous transmission, as in telemetering; also on-the-spot selection of suitable data, as in coincidence methods. Secondly, there is the rapid and precise collation, condensation, and evaluation of available data, as exemplified by punched-card techniques. And, finally, there is the electronic computation of the solution of mathematical equations, which permits the efficient application of theoretical results to given special conditions.

At present, I wish to report briefly on progress in a field of geophysical endeavor with which I have been associated, that is, the inquiry into the nature of the earth's magnetic field. The study of geomagnetism is almost as old as physical science itself, but for a very long time it suffered from a fatal handicap, namely, the rather complete isolation of the phenomenon. Obviously, one cannot make a theory of an isolated fact; scientific theories deal with classes of phenomena, not with single facts. I shall endeavor to show how this isolation has been gradually broken down and a background supplied against which the theoretical interpretation of geomagnetism could be developed. The first event in this series of discoveries was the finding, by Hale and his associates some 40 years ago, in the then fairly new Mount Wilson Observatory, that the dark area of any sunspot, the umbra, carries invariably a magnetic field, which for the larger spots is of the order of a few thousand gauss. It was clear that such fields could not be due to any permanently magnetized material, but that they would seem to indicate the operation of an electromagnetic induction process, such as is used to amplify electrical current in conventional technical dynamos (generators). But the problem of translating the theoretical analysis from a system of rotating wires to the motions of a large-scale fluid turned out to be difficult. Progress has, however, been made in more recent years. A rather cogent reason has been found why large-scale systems should be prone to produce amplification of electromagnetic fields spontaneously. A current flowing in an ordinary conductor in the laboratory decays with extreme rapidity, and so, of course, does the magnetic field of which this current is the source. Now electromagnetic induction occurs when a conductor, say a wire, is moved across a magnetic field. It is necessary that the magnetic field be maintained against spontaneous decay while this mechanical motion occurs. This requires large inductances, realized in technical machines by means of iron cores in the field coils. But other things being equal, the inductance of a body is proportional to the square of its linear dimensions; for conductors of cosmic size, the inductance becomes truly large and a system of electric currents will maintain itself for a long time; during this time, it can be amplified by internal motions of the fluid.

We said that the first step in taking the phenomenon of geomagnetism out of its isolation was to realize its relationship to sunspot (and generally solar) magnetism. The second step occurred soon after the discovery of sunspot magnetism. Seismology had by then developed to a considerable degree of refinement, and the mechanical constitution of the earth's interior was being systematically studied in the early decades of this century. From these studies, there emerged the inference that the earth has a *liquid core*, about half the linear size of the

earth itself. Geochemical investigations then made it extremely likely that this core consists mainly of molten iron and thus is a good conductor of electricity. Now it had long been noticed that the geomagnetic secular variation is an extremely rapid phenomenon. The main periods of its spectrum range from, say, 20 years to 200 years, and this distinguishes the phenomenon clearly from geological processes that require times of the order of many thousands or even of millions of years. After the existence of a liquid core was established beyond any reasonable doubt, the conclusion was drawn that the geomagnetic secular variation must be explained in terms of mechanical motions going on in the core rather than in terms of any process occurring in the solid earth. Later quantitative investigations showed that this model is in agreement with all the known properties of the geomagnetic secular variation. One can thus explain the extreme variability of the geomagnetic field, particularly its more localized "eddies," but this does not necessarily explain the existence of the main dipole field.

Our detailed knowledge of the geomagnetic variation grew apace with the knowledge of the earth's interior. There existed a considerable network of geomagnetic observatories at the beginning of this century, and this was now being supplemented by the expeditions of the Carnegie Institution, bringing back data from the oceans which had heretofore been almost blank on the geomagnetic maps. At the end of the Second World War, E. H. Vestine [see 1 of "References" at end of this article] undertook the huge task of systematizing and evaluating all the known geomagnetic data for the period 1900-1940. The patterns which emerged are basic for physical studies of the geomagnetic variation such as are now under way at various places. They not only shed light on the mechanics of the fluid motions in the core, but also on the electrical properties of the solid parts, the earth's mantle, which the electromagnetic fields must traverse in order to get to the earth's surface. On the basis of these advances, then, the earth's magnetic activity, so far as it arises from the interior (there is also some geomagnetic activity originating in the upper atmosphere that is not considered here), this activity receives its proper setting; it fits without difficulty into the general pattern of the earth's internal constitution as we know it today [2].

A third major advance in the process which took geomagnetism out of its isolated position occurred a few years ago when Babcock [3] succeeded in measuring stellar magnetic fields. These measurements are rather delicate. Their limit of resolution is only about 500 gauss. This means that the line-of-sight component of the magnetic field vector (which is the only component measured) must be at least 500 gauss *in the average* over the star's disk; one may safely expect that the actual absolute value of the field in most of the star's photosphere must be at least some thousands of gauss, a field which in the laboratory can only be produced in the narrow space between the pole pieces of a strong electromagnet. The energy which such a field contains is very much larger than, for instance, the kinetic energy of any motions that can be conceived to occur in the photospheres of these stars; the processes that produce these star-wide fields must be located at considerable depth inside the star. There are rather severe restrictions on our ability to detect such magnetic stars: they must be relatively bright, that is, near-by objects, otherwise the spectral resolution is inadequate. Only stars of certain types

are likely to exhibit magnetic fields on theoretical grounds, a point to which we shall revert. A very large fraction of the stars selected on these principles for observations turned out to have magnetic fields, and Babcock concludes that, on statistical grounds, many if not most of the stars in certain classes must be strongly magnetic. This amounts to an immense number of celestial objects, although our limited observational techniques permit us to analyze only the nearest ones.

It becomes more and more likely, therefore, that under certain conditions large cosmical bodies which are good conductors of electricity develop magnetic fields as a matter of dynamical necessity. Closer study shows that there is apparently no radical difference between the magnetic phenomena in the earth's core and those in the sun and stars. The electrical conductivity of the earth's core is due to its being metallic and that of the sun and stars to thermal ionization, but beyond this there appears to be a great deal of similarity in the basic mechanism. Almost always, when one is dealing with magnetic fields in an electrically conducting fluid of large dimensions, the field and the fluid motion are strongly coupled: the fluid motion changes the strength and magnitude of the magnetic field; the field in turn is usually intense enough to exert mechanical forces that accelerate or decelerate the motion of the fluid. One then speaks of hydromagnetic phenomena or of hydromagnetism in brief. The theory as it has been developed by a number of authors in recent years has many applications to the dynamics of cosmic fluids and to the analysis of electromagnetic fields observed in geophysical and astrophysical investigations [4]. Here we shall confine our interest to the dynamo mechanism.

We have already referred to one indispensable property of any dynamo, namely, that the spontaneous decay of the electromagnetic fields involved be slow, so that the fluid can move about and the field be amplified before it has had time to decay. In the limit where the lifetime of an electromagnetic field is assumed infinite, there exists a simple theorem which describes the behavior of the field: the magnetic field lines change in such a way that they can be thought of as remaining attached for all time to the same individual particles of the fluid. Thus, as the fluid moves and changes its configuration, the field lines are deformed correspondingly. This quantitative result, obtained many years ago by T. G. Cowling, embodies the fundamental principle on which all hydromagnetic dynamos are based. It is itself a simple consequence of classical electromagnetic theory as applied to systems of large dimensions. If in particular the fluid undergoes a shearing motion, the magnetic lines of force will also be sheared and thereby in general be bundled closer together, leading to a local amplification of the field. On the other hand, this process alone cannot give a satisfactory dynamo, because a mere "scrambling" of the lines of force continued indefinitely leads to a magnetic pattern of ever increasing complexity. The phenomenon of free decay thins out the lines of force, and thus a balance is eventually reached in any real dynamo, between the induction mechanism contorting the magnetic field and the decay processes smoothing it out.

The dynamo problem is too difficult to be solved with mathematical rigor. Also, the motions in a conducting fluid which one would deduce from observations

are complex and not readily accessible to analysis. The essentials of a solution were first outlined in 1947 and have since been developed in two directions. One can in the first place emphasize the mathematical aspects, assume a given pattern of fluid motion which one suspects of producing dynamo action and then try to solve the equations. This approach has been taken by Takeuchi and Shimazu [5] and by Bullard and Gellman [6], the latter authors using large electronic computing machinery. So far, the technical difficulties of mathematics have proved too much (the series employed are rather unstable and their convergence is not established). A somewhat different approach has been taken by Parker [7] and this writer. Based on the fact that magnetic fields are so common in celestial bodies, one searches for a general *dynamical* principle underlying fluid motions which deform magnetic fields so as to produce self-sustaining dynamos. This principle is found in the effect of over-all rotation of the system upon its internal fluid motions, that is, in the action of the *Coriolis force*. The result of the analysis is that a regenerative feedback cycle can be constructed by considering the effect of the Coriolis force *twice*; it must explicitly control two different components of the motion. On the basis of a model of this type, it has now been possible to give a semi-quantitative account of all the major observed features of geomagnetism [8].

A good many years ago, Cowling proved that a fluid motion confined to the meridional planes of a rotationally symmetrical figure cannot act as a self-sustaining dynamo. More generally, high geometrical symmetry is unfavorable for dynamo action; a dynamo must be essentially a system of low geometrical symmetry. The Coriolis force produces flow patterns of the required low symmetry. But the Coriolis force does not itself create motion; it merely deflects an already existing one. The next question is therefore concerned with the physical origin of the motions. It may be shown that relatively simple types of motions, such as tides, are inadequate for reasons similar to those that exclude motions of high symmetry. It is generally accepted that the motions conclusive to dynamo action are *convective*, that is, they consist in the rising of relatively less dense material and a corresponding sinking of denser material. This process, conjointly with the action of the Coriolis force upon it, leads to essentially three-dimensional flow patterns. Thus, the simultaneous occurrence of convection and rotation are prerequisites for dynamo action. This result has found an impressive corroboration in Babcock's stellar magnetic data. It is known that in the scheme of stellar spectral classes the so-called "early" type stars rotate very rapidly on the average, and rotation becomes the slower the "later" the spectral type. On the other hand, late-type stars have convective zones surrounding the stable interior, but these zones become the weaker the earlier the spectral type and are absent in the earliest types. Thus, one should expect that the conditions for dynamo action are most favorable in the middle of the spectral sequence and are unfavorable at both ends where either convection or rotation fails. Babcock's data show no magnetic stars of very early or very late types; the majority of magnetic stars are of spectral type *A* and the others of adjacent types, somewhere in the middle of the stellar sequence where both rotation and convection are sufficiently strong.

But we have strayed too far from the earth and shall now revert to it. For a long time, it was assumed that the convective motions in the core responsible

for geomagnetic phenomena are of thermal origin, produced by radioactive heat. While there was no alternate independent evidence for this, calculations showed that the amounts of heat required were very small and might readily be accounted for on plausible assumptions. Recently, however, Urey [9] has thrown doubt on the possibility of thermal convection by showing that, on chemical grounds, the concentration of radioactive substances in the core would be inadequate. This brings to the fore an alternate possibility, namely, that the density differences required are produced by slow, progressive chemical differentiation, such as has been discussed by Urey in connection with the solid parts of the earth. It may be shown that in order to keep the convective regime in the core going, relative differences in density of the order of two parts in 10^9 must be maintained. This may readily be achieved by slow chemical separation in the central parts of the core, where the seismological data show that a separate stratum, the so-called "inner core," exists.

Thus, geomagnetism might have some relationship to geochemistry in a rather unexpected way. Another, much closer connection of these two disciplines appears in the study of "fossil" magnetism [10], which has recently received much attention. The so-called remanent magnetization of rocks has long been considered as indicative of the past condition of the earth's magnetic field, but up to a few years ago there was too much confusion of the data to permit definite inferences. This has changed since Graham [11] succeeded in establishing criteria of stability for the remanent magnetization of rocks, thus permitting us to single out those rocks that are suitable for paleomagnetic investigations. This paper is not the place to discuss the very interesting and often difficult techniques that have of late been developed to elucidate the data of rock magnetism; we shall merely mention what appear at present to be the two principal results. These are not yet established with a certainty beyond any doubt, but the cumulative impact of the more recent measurements is such that the evidence cannot be rejected. It points in the first place to the occurrence of *reversals* of the earth's magnetic polarity. A considerable number of such reversals have been detected through the study of lava flows, as well as of sediments whose remanent magnetic moments are in a direction opposite to that of the earth's present field. The dynamo theory encounters no particular difficulties in explaining such reversals, although a unique model of the reversal mechanism has not yet been established. Owing to the action of the Coriolis force, the earth's magnetic moment can be either parallel or anti-parallel to the earth's angular momentum. There is, indeed, evidence from rock magnetic data to the effect that in the geological past the deviation of the magnetic from the mechanical axis has been considerably less than the present $11\frac{1}{2}$ degrees, which should be thought of as an exceptionally large fluctuation.

In order to account for the peculiarities of climate in paleozoic times, geologists have long ago advanced the idea that the geographical poles have shifted their position in the course of geological history. Now, since the magnetic axis should always have been roughly coincident with the geographical axis, this hypothesis can be tested by determining the direction of the remanent magnetization of ancient rocks. This has been done recently, with the result that the reality of such pole migration is now fairly well established. It appears that in the Pre-

cambrian the north pole was somewhere in the central Pacific and that during the Paleozoic it gradually moved near to the present position; it has not changed much since the early Tertiary. Much active work is now being done in this field, and we may hope to have more and more precise information soon. It seems rather clearly established, however, by now that magnetic studies are also bound to be of considerable importance in the future of geology.

References

- [1] E. H. Vestine, Carnegie Inst. Wash. Pub. No. 578 and No. 580 (1947).
- [2] W. M. Elsasser, Rev. Modern Phys., 22, 1 (1950).
- [3] H. Babcock and T. Cowling, Mon. Not. R. Astr. Soc., 113, 357 (1953).
- [4] W. M. Elsasser, Amer. J. Phys., 23, 590 (1955); *ibid.*, 24, 85 (1956).
- [5] H. Takeuchi and Y. Shimazu, J. Geophys. Res., 58, 47 (1953).
- [6] E. Bullard and H. Gellman, Phil. Trans. R. Soc., A, 247, 213 (1954).
- [7] E. N. Parker, Astroph. J., 122, 293 (1955).
- [8] W. M. Elsasser, Rev. Modern Phys. (to be published 1956).
- [9] H. C. Urey, Ann. Géophys., 11, 65 (1955); see also "The planets: their origin and development," Yale University Press, New Haven (1952).
- [10] S. K. Runcorn, Adv. Phys. (Phil. Mag. Sup.), 4, 244 (1955).
- [11] J. W. Graham, J. Geophys. Res., 54, 131 (1949).

S. CHANDRASEKHAR, University of Chicago, Chicago, Illinois: **The effect of internal motions on the decay of a magnetic field in a fluid conductor.**† The decay of a magnetic field in a fluid conductor with internal motions is considered in case the magnetic and the velocity fields have symmetry about an axis. The underlying characteristic value problems are solved for certain simple velocity fields. The method of solution is based on a new classification of the basic axi-symmetric modes of the magnetic field in terms of Gegenbauer polynomials. The principal conclusion of the paper is that velocity fields of reasonable patterns and magnitudes can alter the time of decay that will obtain in the absence of motions by quite large factors. The bearing of this result on the problem of the origin of the earth's magnetic field is briefly discussed. Certain other related questions are also considered.

H. G. BOOKER, School of Electrical Engineering, Cornell University: **Phenomena of irregular scattering in the ionosphere.** It is the object of this summary to draw attention to the numerous phenomena that involve irregular scattering of radio waves at various levels in the ionosphere. In no case is there a generally accepted quantitative explanation of the phenomenon at the present time. In some cases, there is no agreement even on qualitative cause.

(i) Even for a quiet ionosphere, the simplest radio echo at normal incidence has a fading range comparable with the mean signal, indicating that some kind of irregular scattering is nearly as important as classical internal reflection [see 1 of "References" at end of this summary].

(ii) Under certain conditions, including magnetically disturbed conditions, echoes from the *F* region of the ionosphere become extremely spread in range [2].

†The complete paper will be published in the July 1956 issue of the *Astrophysical Journal*.

The fading of the parts of the echo at different ranges is largely uncorrelated and the fading range is comparable with the mean signal. This phenomenon of "spread *F*" has been known for more than 20 years, but it is still without satisfactory explanation.

(iii) Noise from radio stars received in the VHF band shows twinkling similar to that produced in the troposphere with visual stars [3]. Radio star twinkling frequently shows correlation with "spread *F*" and is believed to be associated with irregularities in the *F* region that are elongated along the earth's magnetic field [4]. Correlation with sporadic ionization in the *E* region also occurs, however.

(iv) Radar echoes from meteor trails, after about half a second, develop irregular fading that cannot be explained in terms of a trail that remains straight [5]. Visual observations of meteor trails likewise indicate twisting of the trail in a manner suggesting atmospheric turbulence at heights between 80 and 100 km [6]. It is presumed that the irregular fading of radar echoes from meteor trails is due to the effect of turbulence on the ionized trail.

(v) At frequencies of the order of 2 Mc/sec, weak echoes can be obtained almost continuously at normal incidence from levels somewhat below the level of reflection from the regular *E* region [7]. The echoes are spread in range, have uncorrelated fading at different heights, and a fading range comparable with the mean signal [8]. It is presumed that they are due to scattering by irregularities of electron density in the *D* and lower *E* regions.

(vi) Above the maximum usable frequency for regular ionospheric transmission, signals can be received at distances from a few hundred kilometers up to about two thousand kilometers, at frequencies up to about 100 Mc/sec [9]. Signals have the fading characteristic of scattering from a large number of irregularities. The height at which the scattering occurs is about 90 km at night, and perhaps a little lower during the daytime [10].

(vii) At times of auroral activity, radar echoes are obtained in the VHF band from regions of the sky that bear some relation to the regions of visual activity [11]. There is sometimes a close correspondence between the regions of visual activity and those from which radio echoes are obtained. However, radio echoes do not usually occur overhead or at short ranges and are mainly confined to the quadrant centered on magnetic north [12]. Fading is of the type associated with random scattering and is at least a power of ten faster than would be expected for a quiet ionosphere. There is a Doppler shift in the frequency of auroral echoes comparable in magnitude to the fading rate. The Doppler shift does not, in general, agree with the rate of change in the range of echoes [13]. The height from which echoes come is almost certainly that of the *E* region.

All of the above phenomena could be explained qualitatively in terms of atmospheric turbulence at ionospheric levels. That such turbulence does exist up to and including the *E* region is not in serious doubt. Whether turbulence can exist in the *F* region, however, is debatable, although the radio data seem to suggest turbulence at this level, especially at times of magnetic disturbance. At present, however, there is no comprehensive theory of ionospheric turbulence capable of presenting all of the above observations as different aspects of a single atmospheric phenomenon.

References

- [1] R. W. E. McNicol, Proc. Inst. Elec. Eng., **96**, III, 517 (1949).
- [2] J. H. Meek, Terr. Mag., **54**, 339 (1949).
- [3] M. Ryle and A. Hewish, Mon. Not. R. Astr. Soc., **101**, 381 (1950).
- [4] A. Hewish, Proc. R. Soc., A, **209**, 81 (1951).
- [5] J. S. Greenhow, Proc. Phys. Soc., B, **65**, 169 (1952).
- [6] W. Liller and F. L. Whipple, Rocket exploration of the upper atmosphere, Pergamon Press, Ltd., London (1954); p. 112.
- [7] W. Dieminger, Physics of the ionosphere, Physical Society of London (1954); p. 53.
- [8] F. F. Gardner and J. L. Pawsey, J. Atmos. Terr. Phys., **3**, 321 (1953).
- [9] D. K. Bailey, R. Bateman, L. V. Berkner, H. G. Booker, G. F. Montgomery, E. M. Purcell, W. W. Salisbury, and J. B. Weisner, Phys. Rev., **86**, 141 (1952).
- [10] D. K. Bailey, R. Bateman, and R. C. Kirby, Proc. Inst. Radio Eng., **43**, 1181 (1955).
- [11] H. G. Booker, C. W. Gartlein, and B. Nichols, J. Geophys. Res., **60**, 1 (1955).
- [12] R. Dyce, J. Geophys. Res., **60**, 317 (1955).
- [13] K. Bowles, J. Geophys. Res., **59**, 553 (1954).

ROGER M. GALLET, Boulder Laboratories, National Bureau of Standards, Boulder, Colorado: **The temperature in the upper levels of the atmosphere.** The theoretical problems of obtaining measurements of the temperature in the upper levels were discussed. The theory of the deviative absorption of radio waves, related to the Coulomb interaction between electrons and ions in the *F2* region, furnishes a relationship depending essentially on the electronic temperature. This gives a new and interesting possibility for making this measurement through the use of radio astronomy techniques utilizing galactic noise. Indications are that information can be obtained concerning the relative variations of the temperature, as well as the gradient of the temperature with altitude. Progress in the theory of the conductivity of a completely ionized gas is needed for improvement in the exact values of the coefficients and for putting the observations on an absolute basis.

L. V. BERKNER, Associated Universities, Inc., New York, N. Y.: Ionospheric research during the International Geophysical Year. As early ionospheric data became available from a few localities over the earth, it became evident that a generalized description of ionospheric behaviour would require observation from a much more tightly spaced network. Subsequently, ionospheric observatories have been installed by many countries, leading to much clarification of difficult problems. The geomagnetic control of ion density of the *F2* layer is now apparent. Certain aspects of ionospheric change with magnetic storms have been defined. Nevertheless, because of glaring gaps in the observing network, many aspects of ionospheric phenomena are not yet clearly defined.

For the IGY, special effort has been made to establish lines of stations at frequent intervals along the meridians of 10° east, 70-80° west, and 140° east. Gap-filler stations will also be located along the equator and in bands around the auroral zone. Consequently, for the first time, we can enjoy the hope that a more complete and rational description of ionospheric phenomena can be obtained. In addition to vertical echo-sounding, particular attention will be given to relation between the changes of ion distribution and absorption of waves in the ionosphere,

both through measurement of intensity of cosmic radio sources of radiation and by measurement of variation of echo intensity.

Of the questions that will be examined, the following are typical examples. Do ionospheric storms associated with magnetic storms spread outward from the poles with time in meteorological fashion? How does the spread of ionospheric changes during ionospheric storms relate to the spread of absorption of waves? How is the distribution of the ionosphere related to the development of auroral phenomena of various patterns and in various localities? What is the character of ionospheric distribution inside the auroral zone, especially during polar night? Just how is the F_2 layer distributed north-south across the region of crossing and the region of maximum separation of the geographic and magnetic equators? Just what are the ionospheric characteristics of the electrojet? Are the observed distributions of F_2 -layer ionization consistent with widespread transport of ions and what pattern of transport is suggested?

The value of the improved network of ionospheric stations will be greatly enhanced during the IGY by related observing networks and augmented observational programs for aurora and airglow, geomagnetism, cosmic rays, solar patrol, and perhaps by the enhanced meteorological program.

The observations during the IGY should be sufficiently complete to provide a real challenge to the theoretician. There is, however, a serious deficiency of opportunity for theoretical workers in the field of outer atmospheric theoretical research. Unless this can be corrected, the full benefits to knowledge of the work of the IGY will not be realized. Therefore, action seems urgently needed to improve the opportunity and support for theoretical work toward synthesizing a more generalized description of related ionospheric, magnetic, cosmic ray, and auroral phenomena, especially as they relate to solar or other extraterrestrial control.

2:00-5:00 P.M.

Merle A. Tuve, Chairman

SYDNEY CHAPMAN, University of Alaska, College, Alaska: The solar corona and the temperature of the ionosphere. L. Spitzer (1949) has pointed out that, if the ionospheric temperature mounts with height as commonly supposed, there will be a notable downward flux of heat, through the E and F layers. D. R. Bates (1951) has discussed the temperature of the upper atmosphere, and has shown that there is some difficulty in explaining whence comes the heat energy lost to the ionosphere by thermal conduction and radiation. It is here suggested that the source may be thermal conduction from the solar corona, extending to and beyond the earth.

The thermal conductivity λ of the coronal gas can be calculated, as the gas may be treated as fully ionized atomic hydrogen: λ depends very little on the density of the gas, but varies with the temperature ($T^0 K$) as $T^{5/2}$. If T_0 is the coronal temperature near the sun, and if the temperature tends to zero at infinity, and if thermal conduction is the only process considered, it appears that T will vary with the distance r from the sun's center as $r^{-2/7}$. Thus, at the distance of the earth, the temperature will be $T_0/4.5$. If T_0 is 10^6 , then at the earth's distance, T will be $225,000^\circ$. The hot gas will warm the ionosphere from the outside, although

the geomagnetic field will reduce the heat conductivity and the heat flow near the earth. The downward flow of heat through the earth's atmosphere, as calculated from assumed data for the F layer, is only 10^{-8} of that flowing outwards from the solar corona. The coronal gas will also warm the surface of the moon and of the planets other than the earth; but they will have little cooling effect on the corona.

If the corona is treated as being in static equilibrium, the number of decimal scale heights between the sun and the earth will depend inversely upon the value of T_0 . If T_0 is 10^6 , the number density in the corona near the earth will be less than the number density of electrons in the space round the earth that has been inferred by Behr and Siedentopf (1953) from their study of the zodiacal light—namely, 600/cc. But if T_0 is 2×10^6 , as some evidence suggests, the number density will be decidedly greater than 600.

Further details and developments of these ideas will be published elsewhere.

References

- Spitzer, L. (1949); *Atmospheres of the earth and planets*, edited by G. P. Kuiper, Chicago, University of Chicago Press.
 Bates, D. R. (1951); *Proc. Phys. Soc., B*, **64**, 805–821.
 Behr, A., and H. Siedentopf (1953); *Experientia*, **9**, 134; see also *Nature*, **171**, 1066.

N. C. GERSON, *Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Massachusetts*: **General circulation of the high atmosphere.** Notwithstanding the vast vertical extent of the atmosphere, regular wind observations have been made only in the lowermost shell, the troposphere. In recent years, however, increasing attention has been given to the pattern of atmospheric movements at much higher altitudes, and particularly in the ionosphere. The observations indicate the presence of drifts, considerable small- and large-scale turbulence, a diurnal trend (presumably tidal in origin), and distinct seasonal variations.

While most studies on movements in the higher atmosphere have been experimental in nature, several theoretical examinations also have been undertaken. This abstract outlines some preliminary deductions concerning the planetary circulation at high altitudes.

In treating the general circulation of the atmosphere, consideration must be given to forces causing or impeding motion on a planetary scale. Accelerations of the atmospheric fluid may be produced by: (a) Gravitational attraction of the sun and the moon; (b) atmospheric pressure gradients; (c) impulse phenomena; (d) frictional effects, including contributions of magnetic viscosity, magnetic drag, etc.; (e) Coriolis force of the earth's rotation; and (f) electromagnetic forces acting on moving charged particles (in the ionic and higher layers).

Neglecting tidal movements, the effect of each force may be examined. Pressure gradient forces may be established through several mechanisms: for example, the unequal absorption of solar radiation over extensive areas; the release of latent energy (of vaporization, ionization, and excitation) and its degradation into heat; and the interaction of air masses having different properties. These reasons give cause to suspect that the general problem of cyclogenesis as known in the troposphere has its counterpart in the mesosphere and ionosphere.

Impulse forces are exemplified by the penetration of matter (meteors, cosmic dust, solar ejecta, etc.) into the earth's atmosphere and the resulting transfer of momentum and energy. With one exception, they may be considered as short-lived atmospheric transients which have no great influence upon the broad circulation pattern. During periods of continuous aurora, however, the total influx of auroral primaries may be considerable and sufficient to modify local and possibly large-scale movements at altitudes well above 100 km.

Frictional forces may be related to the "rigidness" of the atmosphere. At the surface of the earth, the rigidness of the entire lower atmosphere may be considered as essentially 100 per cent (slippage equal to zero per cent); thus, the surface layer as a whole may be regarded at rest with respect to the earth, even though at selected latitudes the slippage may be greater than, or less than, zero. Just outside the atmosphere, however, the rigidness of interplanetary material is zero per cent. In essence, an interplanetary "wind" exists moving from east to west at speeds in excess of 1600 km/hr in the equatorial plane.

Electrons and positive ions play a strong role in describing the rigidness *vs* altitude curve of the atmosphere. For example, in any "wind" it is possible for charged particles, whose movements are constrained by the magnetic field, to move in a direction different from that of the neutral air mass. In the lower ionosphere, where neutral particles predominate, such a difference in direction constitutes a drag on mass movements of the atmosphere. At much higher altitudes, however, the reverse condition may occur; any motion is predominantly one of a conducting fluid in a magnetic field, and the movement of neutral particles represents a drag on hydromagnetic motions.

It is then conceivable that below about 200 km, atmospheric drag, being defined mainly as the relative motion of the earth to a neutral atmospheric gas, is probably small. Above 400 km, however, where the proportion of charged to neutral particles becomes increasingly greater, drag effects may become quite large. The stratum from 200 to 400 km can be considered as a transition zone between regions of low and regions of high magnetic viscosity. The dominant forces influencing movements above 400 km may well be hydromagnetic.

The remaining forces, Coriolis and electromagnetic, act to alter the direction of moving particles.

Although the forces indicated above may initiate atmospheric movements, the general circulation itself must satisfy certain global requirements. First, the difference in the net energy absorbed at low and high latitudes must be removed. Secondly, angular momentum must be conserved, and, finally, the equation of continuity for minor atmospheric constituents must be satisfied.

For example, since the planet and its atmosphere are at a relatively constant temperature over limited intervals of years, the net energy input at any particular point must be zero. However, because of the sun-earth geometry, low latitudes display an annual net gain and high latitudes an annual net loss of radiant energy. The large-scale circulations must allow the latitudinal energy differential to be equalized through the transport of energy polewards during the course of the year.

With regard to angular momentum, observations in the lowermost levels of the troposphere show that the atmosphere displays a slight deficiency of angular momentum at lower latitudes, but an excess at middle, and again a deficiency

at higher latitudes. Present theories imply that the low-latitude general circulation, in acting to "distribute" angular momentum, causes many of the large-scale cyclonic and anticyclonic systems so common to middle latitudes.

A third example of the functional nature of the general circulation includes its influence on minor constituents. As their number densities are sensibly constant, minor atmospheric constituents must exist in equilibrium concentrations at given altitudes and latitudes. In any given stratum, their concentration may be constant, so that the gain from sources equals the loss from sinks and transport. During the year, lower latitudes generally act as source, and higher latitudes as sink, regions for some constituents, particularly those photochemically or endothermically formed. If, as expected, the rate of destruction at higher latitudes exceeds the rate of production, the deficiency must be supplied by transport. In this connection, the relative importance of diffusion and advection must yet be evaluated.

Neglecting gravitational influences of the sun and moon, and considering only the factors discussed above, it is interesting to speculate on a possible analogy of high altitude movements to tropospheric and stratospheric wind patterns. It is conceivable, for example, that drifts in the atmosphere up to 200–400 km may contain well-developed cyclonic and anticyclonic systems and jet streams. Analysis of high-altitude drift data after the tidal components have been removed should reveal whether such patterns exist or not. It is quite possible that in the stratosphere and ionosphere the angular momentum flux is materially different from that found in the troposphere; if so, some change in the character and location of the high altitude cyclonic and anticyclonic systems may be found. Above 400 km, the atmosphere would be expected to appear increasingly viscous and thus display a wind component, which increases with altitude, from the east.

In discussing fluid movement and drifts at the higher altitudes, it should be recognized that the atmospheric medium becomes exceedingly tenuous and rare. The concept of a "wind" moving at 400 km/hr in a gas whose density is of the order of 10^{-9} atmosphere is probably not too clearly visualized. Over 95 per cent of the atmospheric mass lies below 20 km, and well over 99 per cent below 100 km. There is the possibility that some movements deduced from radio-wave probings indicate the motions of electrons and ions (which may be different from that of the neutral particles), or the propagation of an ionospheric "wave."

In summary, the same forces acting on the fluids in the ocean or in the troposphere also act upon the gas in the ionosphere. In addition, the latter is subject to further restraints and forces. It must be agreed that, although not at the present time mathematically defined, a study of motions and the circulation of the high atmosphere is an engrossing, though difficult, task.

JOSEPH W. CHAMBERLAIN, Yerkes Observatory, Williams Bay, Wisconsin:
Present status of theories of the aurora.† It is convenient to consider separately theories concerned in the main with the origin of the primary auroral particles (extraterrestrial or otherwise) and theories dealing with the production of luminosity in the upper atmosphere by primary and secondary particles.

†A more extensive review and comparison of auroral theories is in preparation for "Advances in geophysics," edited by H. E. Landsberg, Academic Press, Inc., New York.

I. ORIGIN OF AURORAL PARTICLES

The leading theories today are concerned with solar-particles streams or with dynamo action in the terrestrial atmosphere. The earlier ultraviolet-light theory of Maris and Hulbert and various suggestions for meteoric origins meet with too many difficulties to be considered seriously.

Solar-terrestrial ion streams—The early “Terrella” experiments by Birkeland inspired the magnificent theory of Störmer [see 1 of “References” at end of this article] on the motion of charged particles under the influence of a magnetic field. Several modifications of the Birkeland-Störmer ideas have been made, principally because of Schuster’s [2] objection that a stream of particles of one sign would disperse too rapidly. However, Störmer’s particle theory gave many impressive explanations of auroral phenomena, which largely explains the close adherence of most current opinion to the particle-stream hypothesis.

The best-known “modern” theory is that of Chapman and Ferraro [3], in which a neutral ionized beam is ejected from the sun by an unknown mechanism. The positively charged ions and electrons all travel with the same speed. For a number of idealized situations, the advance of the stream in the terrestrial magnetic field has been investigated. The theory gives a satisfactory explanation of the first phase of a magnetic storm, and Martyn [4] extended the theory to indicate how an equatorial ring-current might develop from the stream at five or six earth radii. Surface charges on the polarized ring would be unstable and hence would be accelerated to the auroral regions along the magnetic lines of force, striking the atmosphere at roughly 25° from the magnetic pole and with energies around 1 Mev, which are adequate to explain the observed auroral heights.

Bennett and Hulbert [5] have developed a particle-stream theory on the postulate (first made in 1916 by Vegard, [6]) that electrons and protons are traveling with different speeds, but that the beam is electrostatically neutral. The Bennett-Hulbert theory proposes that electrons would be slowed down much more readily than heavy ions on passing through the corona and interplanetary space, and that the resulting strong current holds the beam together (magnetic self-focusing action). This theory has recently been criticized by Ferraro [7], who gives a strong argument that only a negligible net current could exist in the stream. At any rate, in the earth’s neighborhood, the stream would behave somewhat like Störmer’s all-proton beam, although for an accurate description of the orbits it would be necessary to consider the effect of the stream on the earth’s magnetic field.

Difficulties in Störmer’s theory are also inherited by Bennett and Hulbert; namely, the speeds of the incident particles must be about 10^9 cm/sec to explain the lower heights of arcs, but the time delay between solar events and aurorae suggests average speeds closer to 10^8 cm/sec and the observed radius of the auroral zone (on the average about 23°) gives speeds of nearly 10^{10} cm/sec, when interpreted by Störmer theory. Störmer tentatively suggested a ring-current might explain this discrepancy in the radius of the auroral zone. Recent unpublished work by Bennett and Hulbert has attempted to resolve these difficulties by other considerations.

Alfvén [8] has proposed a theory for a particle stream that becomes polarized

by its motion in the solar and terrestrial magnetic fields. A large separation of charge across the polar regions of the earth leads to an auroral-producing discharge along the magnetic lines. Whereas the theory possesses several attractive features, Chapman and Cowling have pointed out serious difficulties regarding the separation of charge.

Atmospheric dynamos—The basic ideas of Balfour Stewart have been elaborated upon in recent years by Wulf and by Vestine. According to Wulf [9], the auroral excitation energy arises from zonal circulation in the *D* and *E* regions: a strong east-west wind in the ionosphere would result in a north-south polarization of charge. If a closed current system could be set up, by means of a north-south return flow of charge at much higher altitudes, Wulf believes a considerable vertical separation of charge could occur. Hence, discharges along magnetic lines of force might give rise to the visual aurorae, while the current systems affect the geomagnetic field.

Vestine [10] has made a start at a more quantitative development of a dynamo theory for geomagnetic disturbances and, in particular, magnetic storms and aurorae. Although the theory does not seem capable of explaining the acceleration of protons in the upper atmosphere, it does provide stimulating new mechanisms for other auroral phenomena. For example, Vestine shows how zonal and meridional winds might set up a strong toroidal magnetic field, around the auroral zone, which would have a strong influence on the orbits of arc-producing protons. Another bold suggestion was that the changes in the toroidal magnetic field with time, due to changes in wind speed, might set up "betatron" acceleration. In this fashion, electrons could be accelerated along the poloidal lines of force (of the earth's main field) to form the rays, when the electrical conductivity becomes sufficiently great. Also, hydromagnetic waves, progressing along the magnetic lines of force, may be responsible for the undulating trains of luminosity seen in active displays. Further analysis of these suggestions would be in order.

II. AURORAL EXCITATION

Homogeneous Arcs—Although some theoretical work on the excitation of arcs by incoming electrons has been done, the neglect of elastic scattering by atmospheric collisions invalidates most of the results. Moreover, the various observations on hydrogen lines in the spectra of arcs strongly suggest protons are a major component of the incident particles.

Chamberlain [11] has discussed the excitation of the hydrogen itself when protons enter the atmosphere. Comparisons of theory with observed brightnesses of aurorae give a measure of the proton flux (10^7 to $10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ for a moderate aurora). The analysis also leads to theoretical luminosity curves in the light of hydrogen, and H-line profiles. To fit both types of data with observation, it seems necessary to postulate that protons enter in spiral paths with *various amounts of pitch* and with a large portion of the protons entering at large angles to the lines of force. Störmer [1] considered homogeneous arcs as produced by particles entering at large angles to the magnetic lines; as the particle-bundles spiral in the atmosphere and the individual protons disperse from the beam, the arc appears diffuse. However, the excitation analyses show that an arc produced by protons entering from

only one angle would be much too narrow [11, 12]. Additional analysis of luminosity curves in other emissions can be carried out with laboratory data on excitation and ionization (see Bates and Griffing [12]). Laboratory experiments of bombardment of air molecules by protons and electrons at various speeds, such as the extensive investigations being conducted by Fan, will increase the potentialities of this method of analysis.

Ray structure—According to Störmer's [1] ideas, rayed arcs result from particles whose orbits bring them more or less straight into the atmosphere along lines of force (instead of at large angles). An excitation analysis of a rayed arc should be possible, but a quantitative comparison of the luminosity curves (especially in the light of hydrogen) between rayed and homogeneous arcs is required.

The long thin rays that appear isolated or in draperies probably have another explanation, and there are reasons for supposing them to be fundamentally quite different in origin from the arcs, which are presumably induced by incident protons. Störmer and Vegard have considered rays as resulting from spiral paths with various amounts of pitch to explain the long luminosity curves. Some of the orbits might even reverse themselves before being stopped in the atmosphere and spiral out again. The analysis should take into account scattering by collisions with air, for the case of incident electrons (which seems most likely). In fact, collisions will so completely dominate the situation that it is not possible to draw any definite conclusions with the existing theory of excitation by "cathode rays" [13].

Another possibility, which has recently received a quantitative development [14], is that rays are electric discharges. The nearly constant brightness over a range of 100 km or so and the [OI] emission-line intensities fit into a consistent discharge theory. More observational tests of the theory are needed, but if the discharge mechanism is correct we must ascertain the source of the potential gradient: does it arise from the difference in depth of penetration of protons and electrons, from dynamo action in the atmosphere, or another undetermined cause? It is also not entirely clear how the discharge initially becomes concentrated along narrow paths—the rays.

General excitation theory—In addition to the above problems on the formation of aurorae, analyses of spectral observations and radar reflections have led to temperatures and electron densities in the upper atmosphere and have provided some information on excitation and de-excitation processes. Studies of latitude and time variations in the spectrum arising from differences in the chemical composition or density or velocity of the particle stream should provide important information for the ultimate auroral theory. For example, excitation analyses, such as those recently carried out by Seaton [15], are desirable from the standpoint of fundamental auroral theory as well as physics of the upper atmosphere, since they can give detailed information about the exciting particles.

References

- [1] C. Störmer, *The polar aurora*, Oxford, Clarendon Press (1955).
- [2] A. Schuster, Proc. R. Soc., A., 85, 44–50 (1911).
- [3] S. Chapman and J. Bartels, *Geomagnetism*, Vols. 1 and 2, Oxford, Clarendon Press (1940).

- [4] D. F. Martyn, *Nature*, **167**, 92 (1951).
- [5] W. H. Bennett and E. O. Hulbert, *J. Atmos. Terr. Phys.*, **5**, 211–218 (1954).
- [6] L. Vegard, *Physics of the earth*, Vol. 8: Terrestrial magnetism and electricity (edited by J. A. Fleming), New York, McGraw-Hill Book Co., Inc., Chap. 11, p. 611 (1939).
- [7] V. C. A. Ferraro, *Indian J. Met. and Geophys.*, **5**, 157–160 (1954).
- [8] H. Alfvén, *Cosmical electrodynamics*, Oxford, Clarendon Press (1950).
- [9] O. Wulf, *J. Geophys. Res.*, **58**, 531–538 (1953).
- [10] E. H. Vestine, *J. Geophys. Res.*, **59**, 93–128 (1954).
- [11] J. W. Chamberlain, *Astroph. J.*, **120**, 360–366 (1954); *ibid.*, **120**, 566–571 (1954).
- [12] D. R. Bates and G. W. Griffing, *J. Atmos. Terr. Phys.*, **3**, 212–216 (1953).
- [13] L. Harang, *The aurorae*, John Wiley and Sons, Inc., New York (1951).
- [14] J. W. Chamberlain, *The airglow and aurora*, (edited by A. Dalgarno and E. Armstrong), London, Pergamon Press, Ltd. (1956).
- [15] M. J. Seaton, *J. Atmos. Terr. Phys.*, **4**, 285–294, 295–313 (1954).

**DONALD H. MENZEL, Harvard College Observatory, Cambridge, Massachusetts:
Astrophysics and generalized gas dynamics.**

The applications of generalized fluid dynamics are, as this conference is clearly demonstrating, essentially without limit. Harvard astronomers entered the field almost ten years ago, with one primary objective: to find an explanation for the peculiar forms and motions of solar prominences. The motion picture records of our cosmic laboratory, the sun, obtained from our observatories at Climax, Colorado, and Sacramento Peak, New Mexico, were furnishing us with a puzzling variety of fluid motions.

The more spectacular forms of solar prominences displayed activity that might be described as explosions, geysers, surges, jets, or ascending arches, if we can extrapolate from terrestrial experience to objects whose linear dimensions are measured in hundreds of thousands of miles. Many of these glowing clouds of hydrogen gas behave like rain-storms, with individual drops a thousand miles or more in diameter and velocities of fall from 10 to 50 km per second. In sunspot areas, prominence activity tends to be much more violent than in non-spot regions. Activity near the poles is different from that in lower latitudes. We find observational evidence of such phenomena as turbulence, convection, shock waves heating by jet action, magnetic focusing, and electromagnetic forces.

A simple application of engineering equations to a highly idealized model gave encouraging results. Electric currents of a magnitude known to be present in the neighborhood of sunspots should produce forces comparable with those of gravitation. The equation of magnetohydrodynamics, solved with simplified boundary conditions, confirmed the early analysis. We seemed to be on our way to an understanding of physical processes in the solar atmosphere.

As we attempted further refinements, such as allowing for finite conductivity of the medium or the upward decrease in density in the solar atmosphere, we encountered serious difficulties. The cooperative behavior of gases at low densities is very different from that at high densities. To represent the behavior over the relevant ranges of density, we have to use a microscopic theory. The basic equations include the Boltzmann transport equation and are non-linear. To solve these equations, one should know the collision parameters for the gases in question.

The equations are difficult to solve and the Chapman-Enskog procedure often does not converge.

Dr. Max Krook, of Harvard Observatory, has developed a new and simple substitute for the Boltzmann transport equation, employing an extension of a procedure commonly used in the analogous case of transfer of radiation. The exact equation of radiative transfer also requires knowledge of the atomic parameters for absorption and emission of radiation. However, a satisfactory solution follows, if we assume that the re-emitted energy consists of two parts: scattered radiation that has a spectral distribution like that of the incident beam, and remitted radiation whose spectral distribution is that of a black body at the local temperature of the gas. The actual emission is represented as a linear combination of the two extremes.

Krook, employing a similar argument, represents molecular collisions statistically as a linear combination of two different mechanisms, one in which atoms are scattered isotropically without change of speed and the other in which atoms are "absorbed" and then "remitted" at the local mean temperature of the medium. This procedure always converges and makes possible the general solution in terms of the coefficients of the linear combination. Krook and his colleagues have applied this technique to various types of non-linear problems, such as shock waves. The method has proved to be a powerful tool and we hope to exploit it further for many types of astrophysical and geophysical problems.

At the observatory, we have studied a large number of special problems, by a variety of techniques. We are beginning to understand the mechanisms that govern such solar phenomena as sunspots, spot variations, prominences and prominence motion, heating of the solar atmosphere and corona by coupling of the convective radiation field (a subject specially studied by Dr. Richard Thomas), and the form and high temperature of the solar corona.

We have looked into the problem of the interplanetary medium, which consists of clouds of moving atoms and magnetic fields. We have examined the interaction of these clouds with the earth's field, and have discussed such effects as the aurora borealis and magnetic storms.

Finally, Dr. Krook and I have been studying the very complicated problem of the emission of radio noise from the sun. One view, commonly accepted, that this emission occurs as the result of plasma oscillations, appears to be untenable. Ordinary plasma waves are longitudinal and there seems to be no way of getting them to radiate away sufficient energy. However, if a magnetic field is present, we note that the longitudinal vibrations tend to be converted into transverse ones. The calculation of the details is extremely difficult. We visualize that some deep-seated mechanical shock occurs, which spreads out from the source. As it progresses toward regions of lower density, the amplitude increases and finally the original magnetohydrodynamic shock wave is completely converted into electromagnetic radiation as it escapes from the solar atmosphere.

The foregoing cases illustrate the application of generalized gas dynamics to astrophysical problems. In the near future, we should expect to allow for the coupling of the mechanical and radiation fields, where part of the gas excitation is due to radiation and part to collision with atoms in the convective motion.

WILLARD H. BENNETT, *Naval Research Laboratory, Washington, D. C.*: **Solar proton-stream forms as related to the aurorae.** A tube has been developed which produces accurately to scale the orbits of individual charged particles moving in the magnetic dipole field of the earth. This tube has been named the Störmertron after Carl Störmer, who computed many of these orbits. Movies have been made of the progressive changes in shape of streams of charged particles shot out of a spot on the surface of a rotating sun towards the dipole field of the earth. These are qualitatively correct for the large currents of protons assumed in the solar proton theory of the aurora to be swept sidewise past the earth by the sun's rotation.

Some of these movies were shown. These exhibited many of the orbits already calculated by Störmer and other investigators, while many other orbits were shown which have been too complicated to calculate. In addition, the movies showed the formation of rings from particles scattered out of the incoming stream and into captive orbits.

This technique involving the Störmertron tube used as an analogue computer may be applied to other problems, such as the investigation of the various models proposed for the eruption of ionized material from sunspots and other places on the surface of the sun. As such, the technique should be a useful adjunct in theoretical geophysics.

ROSS GUNN, *Office of Physical Research, U. S. Weather Bureau, Washington, D. C.*: **The basic physics of atmospheric processes.** Real advances in all branches of geophysics rest securely on the laws and applications of basic physics. Our interest in geophysics has not been the collection and organization of observational data, but rather in studies of the fundamental processes responsible for the observed physical phenomena [see 1, 2, 3, 4, and 5 of "References" at end of this article]. The theoretical geophysicist is really successful in this work only if he succeeds in establishing a simplified perspective and quantitative framework upon which the diverse observations of nature may be systematically assembled. It is clear, therefore, that theoretical geophysics will contribute to the advancement of our basic understanding only to the extent this work is interwoven with the work and observations of the experimenter. Theory and experiment constitute a powerful team.

Great unexplored areas of broad scientific interest in geophysics still exist that promise much in extending our fundamental understanding of the earth. Studies of the basic physics of weather processes promise to be important in man's understanding of his environment. Much study has already been devoted to the dynamics of atmospheric motions and turbulence, on the properties of high atmosphere, and the ionosphere. On the other hand, relatively little competent scientific effort has been expended on the analysis of the basic weather processes, such as the dynamics of rain formation, cloud stability problems, and the increasingly important problems of atmospheric pollution. There is little hope of man controlling or modifying his meteorological environment unless he clearly understands the basic dynamics of every weather process. This field of science is of great importance and relatively untouched.

The Division of Physical Research in the Weather Bureau has specialized in studies of the precipitation problem and has contributed especially to a broad understanding of the physical properties of freely falling water drops and droplets. Some of our earlier work determined the aerodynamic properties of drops and their velocity of fall in stagnant air as a function of the drop size and the ambient air density. One aerodynamic characteristic of freely falling drops that we observed was the curious oscillation and random lateral drift imposed on droplets of a certain size. Investigations showed that water droplets, of about 1/2 milligram mass, shed vortices to the environmental air at a frequency that corresponded to the natural frequency of oscillation of the droplet [2]. Excessive "wing flutter" accordingly developed and the aerodynamic behavior of such droplets is highly erratic.

Detailed theoretical and experimental analyses of the rate of droplet evaporation and condensation in various environments have been determined and summarized. Elementary aerodynamic principles permitted us to determine the influence of droplet motions on the vapor gradients surrounding freely falling droplets, and through these the factors that controlled evaporation and condensation. The experimental results of this investigation were expressed in analytical form that has been of considerable value to the meteorological physicist. The evaporation or condensation of a drop normally increases or decreases its temperature, and we have, accordingly, determined the dependence of droplet temperature upon time and the physical properties of the environment. Theoretical expressions for the relaxation time of droplets and their final equilibrium temperature were also determined and compared with measurement.

One of the great problems of physical meteorology is to understand in detail how cloud droplets grow to form ordinary rain. Thermodynamic and experimental arguments show clearly that the principal mode of growth is by the association of the cloud droplets. The larger and more rapidly falling cloud droplets overtake the smaller ones and successively associate with a large number to form a bigger drop. The dynamics of this process has been widely studied, but progress has been slow. Recently, we have developed elegant experimental methods of studying the process and have in preparation a number of papers on this important subject.

During the last few years, I have been interested in determining, both experimentally and theoretically, the influence of electrification on precipitation processes, on cloud stability, and on suspended pollution in the lower atmosphere. One aspect of these problems is of sufficient interest to review briefly at this time; namely, the electrification of cloud droplets and raindrops. Very substantial progress has been made on this subject during the last year. A large number of laboratory measurements of the electrical charges carried by artificial cloud particles shows that most clouds are electrified, each typical particle carrying some eleven elementary charges. About half the droplets carry positive charges and the other half negative charges. We have found experimentally that cloud droplets produced by any means whatsoever—spraying, disruption, or by condensation—all exhibit the same type of distribution of electrical charge after they have been exposed for sufficient time to the normal ionization of the atmosphere. The initial electrification of sprayed droplets, silica dusts, condensed sulphur,

etc., may be extremely large or zero, yet when such particles are exposed to copious ionization, all droplets of the same size exhibit the same distribution of droplet charges. This fundamental observed fact led us to investigate in some detail the diffusion of light atmospheric ions onto cloud droplets and contamination particles in the atmosphere. Following through the ordinary laws of diffusion, it has been possible to show that the fractional number of cloud droplets that carry a given charge is a Gaussian-like function of the number of elementary charges carried by each. This distribution is symmetrical with respect to zero charge when the electrical conductivities of the positive and negative light ions are identical. However, it is observed that if the positive light ion conductivity (for example) exceeds that of the negative, then the distribution is systematically displaced towards positively charged droplets. Using straightforward principles, a fundamental aerosol equation has been worked out which describes very well, indeed, the observed distribution of charged droplets in any cloud [4]. According to these investigations, the ratio of the number of droplets per unit volume carrying x elementary charges F_x to the total number per unit volume F_t is

$$\frac{F_x}{F_t} = \left[\frac{e^2}{2\pi a k T} \right]^{1/2} \exp \left[-\frac{\left(x - \frac{akT}{e^2} \ln \left[\frac{n_+ u_+}{n_- u_-} \right] \right)^2}{\frac{2akT}{e^2}} \right] \dots \dots \dots (1)$$

where e is the elementary charge, k is the Boltzmann constant, T the absolute temperature, n_+ and n_- the positive and negative light ion densities, and u_+ and u_- their respective mobilities, while a is the radius of the droplet. The equation has been verified by many experimental measurements.

As a consequence of the equilibrium established by ions bombarding the cloud droplets, we have been able to show that there is usually an *equi-partition* established between the mean electrostatic energy of the *cloud particles* and the *thermal kinetic energy* of the *bombarding ions*. Thus, it is found that [4]

$$\frac{\bar{q}^2}{2a} = \frac{\pi k T}{4} \dots \dots \dots (2)$$

where \bar{q} is the mean charge on the droplets, *irrespective of sign*. A consequence of our investigation is that in typical clouds the observed electrification is due principally to the presence of ions established in the atmosphere by cosmic rays and radioactivity. In thunderstorms, other auxiliary sources of ionization are normally present.

It is fair to state that the above formulation of the electrification processes in clouds has been extremely useful in understanding a number of electrical effects that frequently accompany precipitation. For example, it is easy to see that a raindrop falling down through a typical cloud will be bombarded by cloud droplets that are themselves electrified. This bombardment statistically electrifies the falling *rain* and establishes another approximate equi-partition in which the *electrostatic energy of the raindrop* approximates the mean *kinetic energy* of the *cloud droplets relative to the moving larger raindrops*. The deduced expressions agree with the observations [5].

Separation of free electrical charge normally accompanies the falling of electrified rain and electric fields sufficient to produce lightning are frequently observed. These fields interacting with the electrified cloud droplets contribute to their systematic motion and increase the rate of cloud coagulation. Quantitatively formulating these ideas one may show that when the electric field in the atmosphere exceeds 600 volts per centimeter, a common value in thunderstorms, the precipitation of the cloud by electrical processes may exceed that promoted by gravitational phenomena [6].

Our analysis of the electrification of cloud droplets in rain is consistent with a large body of observed data, and establishes beyond reasonable doubt the importance of ionization and other subsidiary electrical effects in the lower atmosphere and in weather processes. Electrical effects play an important role, not only in active thunderstorms, but in probably all precipitation processes. This means that many of the over-simplified concepts of the meteorologist must be re-evaluated and the relative importance of mechanical and electrical effects determined.

The diffusion of ions onto cloud droplets and other particles in the atmosphere is capable of explaining in some detail volcanic lightning and, of course, ordinary lightning storms. We are presently engaged in the analysis of these phenomena, and the work will be published shortly. Because of the universal character of the electrification of particles in any ionized environment, it is a fair inference that thunderstorm *electrification* somewhat like that we see on the earth *will be present in the atmospheres of any other planets or stars* in which condensed particulate matter systematically is formed and transferred to its surface by gravity. Thus, the work that we have been doing in the earth's lower atmosphere and which is accessible to controlled experimentation, may be applied to the basic physics of planets or other stellar bodies. Such research, therefore, is of fundamental importance in advancing man's understanding of his physical environment.

This brief review emphasizes the importance of adequate analysis coupled with a forward-looking research program designed experimentally to test the ideas as they are developed.

References

- [1] R. Gunn, Quantitative aspects of juxtaposed ocean deeps, mountain chains and volcanic ranges, *Geophysics*, **12**, 238-255 (1947).
- [2] R. Gunn, Mechanical resonance in freely falling raindrops, *J. Geophys. Res.*, **54**, 383-385 (1949).
- [3] G. D. Kinzer and R. Gunn, Evaporation, temperature and thermal relaxation time of freely falling waterdrops, *J. Met.*, **8**, 71-83 (1951).
- [4] R. Gunn, The statistical electrification of aerosols by ionic diffusion, *J. Colloid Sci.*, **10**, 107-119 (1955).
- [5] R. Gunn, Raindrop electrification by the association of randomly charged cloud droplets, *J. Met.*, **12**, 562-568 (1955).
- [6] R. Gunn, Droplet electrification processes and coagulation in stable and unstable clouds, *J. Met.*, **12**, 511-518 (1955).

HORACE R. BYERS, *University of Chicago, Chicago, Illinois: Some problems relating to precipitation mechanisms.* The two principal mechanisms for the growth of cloud droplets to precipitation size—the Bergeron-Findeisen process and the growth by coalescence on drizzle-size drops grown from giant nuclei—are in

competition with each other under conditions commonly found in cumulus clouds. Growth curves of droplets and crystals in the ranges of temperature, particle size, and liquid-water content characteristic of such clouds in the continental United States during summer have been computed by Braham and Sievers (1956).

Crystals in the form of hexagonal plates of 2.5 microns initial radius are allowed to grow theoretically at various subfreezing temperatures in a cloud consisting predominantly of supercooled droplets and at 100 per cent relative humidity with respect to liquid water. The growth is by water-vapor diffusion, followed by riming through collision with the liquid cloud droplets after a certain crystal size is attained. Under the same ambient conditions in the cloud, growth curves of liquid drops of initial radii of 20 microns, 30 microns, and 40 microns are computed. These are sizes measured by the University of Chicago-Air Force group in appreciable numbers among the droplet populations of trade-wind cumulus clouds in the vicinity of Puerto Rico and in cumulus congestus (large cumulus not precipitating) clouds during summer in the central United States and to some extent in Arizona. The growth is by collision and coalescence with the prevailing smaller droplets, with respect to which the larger ones have an appreciable falling speed.

At the higher subfreezing temperatures, such as -5°C , the drops of 40 microns initial radius are in a favorable competitive position for growth, especially at higher liquid-water contents in the cloud. These are the conditions for which artificial precipitation inducement through the ice-crystal phase has been advocated. Thus, some doubt is cast on the efficacy of the treatment on summer cumulus. It is believed that the assumptions made in the computation are more favorable to the ice-crystal growth than to the all-liquid process, and therefore provide a stringent test for the latter.

Flight measurements, including airborne radar data, on hundreds of cumulus clouds traversed by the Air Force-Chicago group show (1) that in the tropical ocean areas of the West Indies no cumulus clouds have to rely on the ice-crystal or Bergeron-Findeisen mechanism for precipitation initiation, since all of them lie below the freezing level when rain starts; (2) that in the central United States the conditions would lead one to believe that in summer cumulus the all-liquid and the Bergeron-Findeisen starting mechanisms are on about an equal footing, and (3) that in Arizona and New Mexico the conditions in summer cumulus are such as to suggest that the Bergeron-Findeisen process has the advantage in precipitation initiation, although the all-liquid process is possible in many cases. The Arizona and New Mexico data were obtained largely from ground radar and visual or camera triangulation at the Institute of Atmospheric Physics, University of Arizona, as yet unpublished, and at the New Mexico Institute of Mining and Technology (Braham, Reynolds, and Harrell, 1951).

References

- Battan, K. J. (1953); Observations on the formation and spread of precipitation in convective clouds, *J. Met.*, **10**, 311-342.
- Braham, R. R., S. E. Reynolds, and J. H. Harrell, Jr. (1951); Possibilities for cloud seeding as determined by a study of cloud height *versus* precipitation, *J. Met.*, **8**, 416-418.
- Braham, R. R., and J. R. Sievers (1956); Paper presented at joint meeting of Physical Society and Royal Meteorological Society in London, January 1956.

SCOTT E. FORBUSH, *Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.*: **World-wide variations in cosmic-ray intensity.** During the past two decades, Compton-Bennett cosmic-ray ionization chambers have been in practically continuous operation at Godhavn (Greenland), Cheltenham (Maryland), Huancayo (Peru), and Christchurch (New Zealand). For shorter periods, such meters have also operated in Mexico, D. F., and at Climax, Colorado. After correction for barometric effects and seasonal variations of meteorological origin, it is found that, except for solar flare effects, the major changes in cosmic-ray intensity are world-wide. In many magnetic storms, the cosmic-ray intensity decreases with the onset of the storm and recovers to normal (in several days) at about the same rate as the earth's magnetic field. However, the ratio of the changes in daily means of cosmic-ray intensity to those in the horizontal magnetic intensity at Huancayo (which are a measure of the storm field) varies from storm to storm. Indeed, magnetic storms occur with no detectable decrease in cosmic-ray intensity. Also one large decrease in intensity occurred¹ in February, 1946, after which the intensity remained below normal for many months. When pooled for each year, the standard deviation of daily means, from monthly means, of cosmic-ray intensity is several times greater near sunspot maximum than at sunspot minimum. Also the annual means of cosmic-ray intensity are at all stations about four per cent less¹ near sunspot maximum than at sunspot minimum. There is also a 27-day quasi-persistent variation in cosmic-ray intensity, opposite in phase to that in magnetic activity. Many of these phenomena are perhaps due to variations, with solar activity, in the density and strength of magnetohydrodynamic clouds in the earth's orbit.

J. A. SIMPSON, *Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*: **The effective geomagnetic field coordinates for cosmic-ray particles.**

I

At present, the geomagnetic coordinates used to describe the spatial intensity distribution of the cosmic radiation are derived from world-wide surface measurements of vector field-intensity. However, since the cosmic-ray particles begin to interact with the external field of the earth throughout a large volume extending a considerable distance from the earth, these particles may be utilized as "probes" to explore the otherwise inaccessible magnetic field around the earth. The fundamental question then arises: is the description of the outer magnetic field required to account for the terrestrial distribution of cosmic-ray particles the same as the field distribution computed from surface magnetic measurements?

In this paper, we shall only consider the location of the geomagnetic equatorial plane derived from cosmic-ray observations and the implications of these results for a world-wide system of cosmic-ray geomagnetic coordinates effective for cosmic-ray particles. We shall not be concerned here with the longitude effects of cosmic-ray intensity, which is strongly influenced by quadrupole terms in the geomagnetic field, but, instead, we shall examine the location of cosmic-ray intensity minima

¹S. E. Forbush, J. Geophys. Res., 59, 525-542 (1954).

(derived from latitude curves) around the earth—we define the equatorial plane as the plane passing through these intensity minima [see 1 of "References" at end of paper].

The secondary component of cosmic radiation generated within the atmosphere was measured by using a neutron-intensity monitor carried across the geomagnetic equator. The work which is being reported here was done in collaboration with K. B. Fenton, and with J. Katzman and D. C. Rose of the National Research Council of Ottawa, Canada. Two of the measurements were made possible this past year 1954–55 by the Antarctic Expedition of the U.S.S. *Atka*, which crossed the equator at 30° west and 100° west longitude. Complete details on the instrumentation, pressure correction, and two-hemisphere sea-level latitude curve have been published [2]. In addition, neutron-intensity observations in aircraft at 78° west longitude have been available since 1948 [3]. These three equatorial crossings have provided us with intensity minima free of atmospheric influence and primary intensity variations. The results for December 1954 and March 1955 are plotted in Figures 1 and 2. In Figure 3, the positions of these minima are plotted on geographic coordinates. The positions of the centered and eccentric geomagnetic dipole-field equators derived from surface magnetic-field measurements are shown

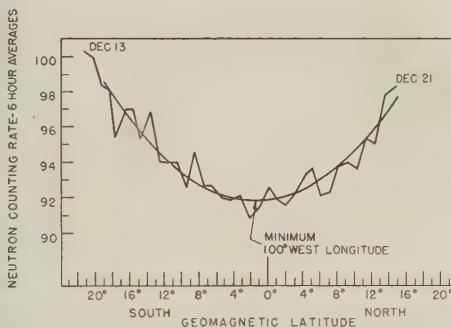


FIG. 1—Sea-level neutron intensity measured December 1954 near the geomagnetic equator. The smooth curve is the least squares fit to 36 points from the data: $= 91.85 + 0.0597 + 0.0216^2$.

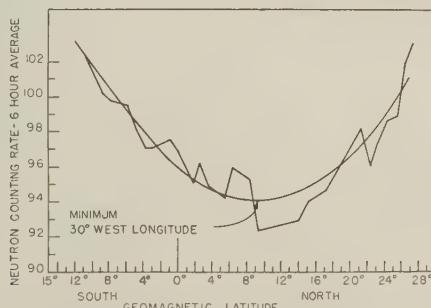


FIG. 2—Sea-level neutron intensity measured March-April 1955 near the geomagnetic equator. The smooth curve is the least squares fit to the data: $= 95.95 - 0.409 + 0.022^2$.

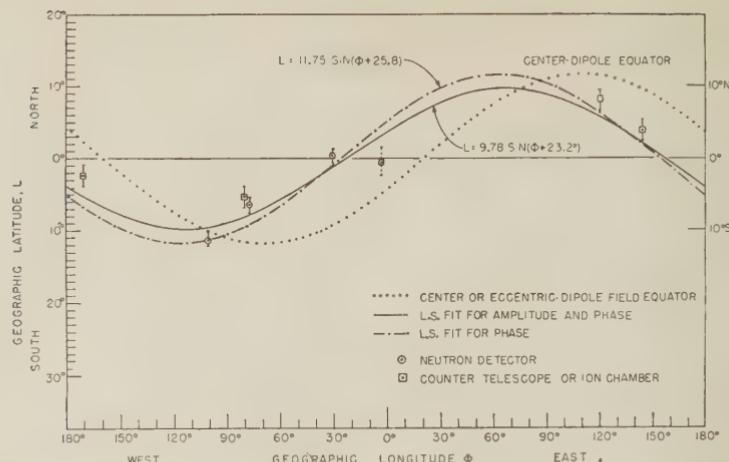


FIG. 3.—The geographic coordinates for the minima of cosmic-ray intensity are shown both for neutron and meson intensity data. The presently accepted position of the geomagnetic equator for both magnetic and cosmic-ray studies is shown as a dotted-line curve. The effective cosmic-ray equator derived from measurements is shown as the broken-line curve, or the solid curve.

The inclined equatorial plane appears to be shifted *westward* approximately 40 to 45°.

as a common curve in Figure 3, because of the small differences between them. The discrepancies between the cosmic-ray and magnetic-field observations are obvious.

II

We have found it possible to go back into the literature over the past 20 years and select the geomagnetic equator crossings obtained by other observers using charged particle detectors. The deviations $\Delta\lambda$ of the observed cosmic-ray intensity minima from the accepted geomagnetic dipole equator are shown in the Table 1.

TABLE 1.—*Location of minimum cosmic-ray intensity*

(The difference between the positions of the geomagnetic equator and the effective cosmic-ray equator is $\Delta\lambda$, with $+\Delta\lambda$ placing the cosmic-ray equator north of the geomagnetic equator.)

No.	Reference	Longitude	$\Delta\lambda$	Date
1	*Clay, <i>et al.</i> [5]	3W	+4	1933
2	U.S.S. <i>Atka</i>	30W	+9	1955
3	Simpson [3]	77W	+4	1948
4	Johnson and Reed [6]	80W	+5	1935
2	U.S.S. <i>Atka</i>	100W	-1	1954
5	Compton and Turner [7]	170W	-4	1936
6	Law, McKenzie, and Rathgeber [4]	145E	-6	1948
7	Sekido, Asano, and Masuda [8]	121E	-3	1937

*This point is somewhat uncertain.

If we assume that these data prescribe the equatorial plane for the external magnetic field of an eccentric and tilted dipole, then they should define an almost perfect sine curve when plotted on geographic coordinates. We have fitted the sine curve by the method of least squares under two different assumptions. In one case, we have fitted a sine curve to the data, assuming that the amplitude is the same as that given by the geomagnetic-field data and have adjusted the phase of the curve. For the second curve, we have fitted both the amplitude and phase of the sine curve to the data. These results imply that the location of the dipole magnetic moment vector required to satisfy the deflection of cosmic-ray particles is to be rotated westward $\sim 40\text{--}45^\circ$ without necessarily changing the inclination or eccentricity. This is in disagreement with the established position of the dipole based upon surface magnetic-field measurements, and we shall return to this discrepancy later in our discussion.

We have been able to study other types of cosmic-ray experiments, such as the geomagnetic cut-off of heavy nuclei in the primary radiation and the east-west effect on cosmic rays observed by other cosmic-ray groups. All of the evidence supports the view that it is possible to account for the enormous cosmic-ray results obtained by these observers on the basis of this new effective geomagnetic coordinate system.

III

Since we know that the field at the surface of the earth is well established [9], the discrepancy lies in the outer regions where interplanetary matter is important. The physical picture which one develops is that of the earth in a highly conducting interplanetary medium. Because of the rotation of the inclined magnetic dipole field, this outer field interacts with the ionized medium—the interaction imparting a westward drag upon the magnetic lines of force. The dynamics of this outer region are not understood at present, though it is likely that the search for the explanation of the effective dipole equator lies in this direction.

Since the earth is in an ionized medium and the possibility exists for an outer ring-current, it is highly unlikely that the incoming cosmic-ray particles experience the field distribution of a perfect magnetic dipole. Therefore, the sine curve plotted in Figure 3 must be considered as an approximation to the exact equator for the new effective geomagnetic coordinates.

Details of this research have been submitted for publication in *Physical Review*.

References

- [1] J. A. Simpson, F. Jory, and M. Pyka, *J. Geophys. Res.*, **61**, 11 (1956).
- [2] K. B. Fenton, J. Katzman, J. A. Simpson, and D. C. Rose, Proc. International Conference on Cosmic Rays, Guanajuato, Mexico (1955).
- [3] J. A. Simpson, *Phys. Rev.*, **83**, 1175 (1951).
- [4] P. G. Law, C. D. McKenzie, and H. D. Rathgeber, *Aust. J. Sci. Res., A*, **2**, 493 (1949).
- [5] J. Clay, *Physica*, **1**, 369 (1934).
- [6] T. H. Johnson and D. N. Reed, *Phys. Rev.*, **51**, 557 (1937).
- [7] A. H. Compton and R. Turner, *Phys. Rev.*, **52**, 799 (1937).
- [8] Y. Sekido, Y. Asano, and T. Masuda, *Sci. Papers, Inst. Phys. and Chem. Res.*, **40**, 439 (1943).
- [9] E. H. Vestine and others, *Carnegie Inst. of Wash. Pub.* No. 578 and No. 580 (1947), and references therein.

E. H. VESTINE, *Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.*: **Some theoretical problems in geomagnetism.** Schuster, Schmidt, and Bauer have demonstrated that the geomagnetic field measured over the earth's surface can be separated by means of potential theory into parts of origin external and internal to the earth. This solution provided by theory is unique, as was shown by Gauss. A recent evaluation shows that about 99 per cent or more of the main geomagnetic field originates from sources within the earth. From potential theory also, world-wide charts of the geomagnetic secular change of the main field can be interpreted in terms of simple sources within the earth. If these sources, inferred from analytic continuation of the field, approximate to singularities such as dipoles, the depth of important sources cannot usually be greater than the estimated depth of the singularities. This has been shown by McNish, and more recently by Runcorn and Knapp. The theoretical extrapolation downwards from the earth's surface was also done by the writer and others using spherical harmonic analyses, and all results suggest the outer part of the earth's central core as the location of major sources. The patterns of geomagnetic secular change suggest that the sources are moving rapidly within the earth, and hence Elsasser proposed that these are carried by fluid moving in the earth's central core. The theoretical methods used in studying such problems are those of potential theory and fluid dynamics in which everyday applications are also made in meteorology and oceanography. Hence, this part of geomagnetism has an affinity of theoretical interest with these subjects. In fact, the reality of fluid motions in the core seems established from an estimate made of the variable rate of westward drift of the geomagnetic field. From hydromagnetic considerations, a variable rate of westward drift of the geomagnetic field should imply corresponding mass motion and hence angular momentum changes of the core. A comparison of these experimental values for geomagnetism with those found by Brouwer for astronomy shows that the variations in the rate of the earth's rotation deduced by the astronomers seem readily explained by the core motions. In fact, other motions of the core can explain year to year shifts of the geographic poles of the earth, off the axis of rotation, as a consequence of gyroscopic theory developed and applied by Munk and Revelle. It appears reasonable to say that experimental and theoretical seismology can with good justification lay claim to being the major contributor to our knowledge of the earth's interior. However, the available information on the variation of electric conductivity with depth arises from the theory of electromagnetic induction, applied to time variations of geomagnetic fields arising from sources external to the earth. Additional information arises from quantum mechanics and the theory of solid state physics, as Elsasser has remarked earlier.

The profusion of geomagnetic time variations, other than secular changes, measured at the earth's surface are linked in time with related changes in aurora, the ionosphere, cosmic rays, solar changes, and again with the flow of electrically conducting air driven by wind-producing forces in the ionosphere. This is another area in which experts, theoretical and experimental, can profitably work together. It seems again reasonable to remark that theoreticians in these various fields have close mutual interests, and that progress can be expedited by such men working

together on similar or the same problems in highly enjoyable fashion in an institute concerned with theoretical problems.

The only theory of magnetic storms that has arrived to at least an initial state of development is that of Chapman and Ferraro. According to this theory, a principal part of the storm field arises from electric currents in solar streams and subsequent effects of streaming particles. An alternative view at present enjoying more limited favor is a dynamo theory, now in a state of development perhaps better described as hypothesis. Many immediate and obvious opportunities exist for using statistical aspects of the now extensive geomagnetic data in improving our understanding of magnetic storms. For instance, surface data can indicate whether or not the sudden commencement and initial phase of magnetic storms can arise from electromotive forces originating mainly in polar auroral regions.

Existing published data, especially in Europe, provide an attractive opportunity for using the theory of electromagnetic induction in deducing local particulars of the electrical conductivity of the outer mantle there. It would be very interesting to compare such results with findings for other areas. In conclusion, it appears that a high opportunity exists in our epoch for extending the frontiers of our knowledge of geophysics, using the theoretical approach. A good way to support and encourage more theoretical effort would be afforded through some institute, or institutes, of theoretical geophysics.

A. G. McNISH, *National Bureau of Standards, Washington, D. C.: The motions of the F-region associated with polar magnetic disturbances.** A. G. McNish amplified some of the remarks by Vestine. He also reported on changes in *F*-region height associated with geomagnetic variations at the equator. In middle latitudes, a current study shows that pronounced fluctuations in *F*-region critical frequency appear at times of magnetic intensifications or bays near the auroral zone. The effect noted is explained by an electric field originating near the auroral zone. He also discussed the importance of understanding the formation of the ionospheric layers for purposes of predicting radio-propagation conditions.

J. R. BALSLEY, *U. S. Geological Survey, Washington, D. C.: Review of rock magnetism.* Scientists interested in the origin of the earth's magnetic field have turned to measurements of the magnetism of rocks for corroboration of their theories. By various tests, it has been shown that the fine red sandstones have the most stable magnetizations, and measurements on these rocks in England and the southwestern United States indicate a gradual shift of the magnetic pole from the center of the north Pacific Ocean in late Precambrian through Japan and Siberia to its present position. If measurements now being made in Africa and India agree, such a shift of the pole can be considered confirmed.

In the course of these studies, several examples were discovered of magnetizations essentially opposite to the present or shifted direction of the earth's field. One possible explanation of this is that the earth's field was reversed at the time the rocks were magnetized.

*Abstract not supplied by author, but furnished from notes taken during the conference.

However, studies on a suite of metamorphic rocks from the Adirondack Mountains have shown that the direction of magnetization is related to the composition of iron-titanium oxide minerals in the rocks; normal magnetization for rocks containing magnetite and reversed magnetization for rocks containing mixtures of hematite and ilmenite. Other studies on folded sandstones in California have shown that the magnetization is related to later deposition of iron oxide minerals in the interstices between the grains and was not developed at the time the sandstone was deposited.

Most of the minerals involved in the magnetization of rocks are ferrites and are ferrimagnetic or antiferromagnetic rather than ferromagnetic. Néel has predicted that certain types of ferrites can demonstrate self-reversal, and numerous artificial compounds have been developed which verify his conclusions. To date, no isolated homogeneous natural minerals have been discovered that exhibit this property, but a few rocks have demonstrated it.

The geologists and sedimentary petrologists are not yet able to determine at what time the fine red sandstones became red, that is, at what time the original iron constituent became hematite, and it is not yet possible to determine what chemical and mineralogical changes have occurred since the original formation of the rock.

In the light of the several possible explanations for the self-reversal of natural rocks, particularly those containing hematite, one cannot at this time categorically state that the reversed magnetization of a rock has been produced by a reversed field of the earth. If, as above, world-wide measurements of accurately dated geologic formations show a clear correlation of reversed magnetization to particular geologic ages, the reversal of the magnetic field could be confirmed.

SETH B. NICHOLSON, *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California,* AND OLIVER R. WULF, *U. S. Weather Bureau, California Institute of Technology, Pasadena, California.*: **The universal-time diurnal variation of irregular geomagnetic fluctuations.** A study of the diurnal variation of the irregular geomagnetic fluctuations in moderately low latitudes, earlier reported (Nicholson and Wulf, J. Geophys. Res., 60, 389, 1955, and Science, 122, 879, 1955) for all days of the nine years 1940-1948, has been made for the five disturbed days of each month for these same years. The eight daily *K*-numbers (3-hour-range indices) for six observatories (see first reference) fairly well distributed in longitude have been used in this work. An average local-time and an average universal-time variation have been formally obtained from these data.

The local-time variation is approximately that to be expected from the work of earlier investigators, with a minimum in the early forenoon and a maximum in the late evening. It shows but little annual variation.

A universal-time variation has been found in this work and is especially prominent in the results for the five disturbed days. It shows a marked annual variation.

We have suggested that the local-time diurnal variation arises from electromagnetic damping of air motions in the earth's permanent field by solar-produced daytime ionization in the lower ionosphere. Some support is given to this suggestion by the indication that the annual change of the universal-time diurnal variation has an asymmetry at least roughly similar to that of the earth's permanent field.

Wednesday, February 1, 8:00 P.M.

Members of working committees met as directed by their Chairmen

Thursday, February 2, 9:00 A.M.-12:30 P.M.

Harold C. Urey, Chairman

HOWARD E. TATEL, *Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.*: **Problems in continental structure.** The history and structure of the earth is surprisingly complex and inaccessible. Our sensing methods are sometimes imperceptible and the far reaches of geologic time defy our imagination. But we are not fazed by such obstacles. Because of these great difficulties, we try to fragment the problems, but the basis of our inductive theories is never too broad and, being somewhat indefinite, they sometimes do not lead to the incisive determinations we are all so familiar with in the experimental and deductive sciences. As an example, consider the problem of the formation of the continents.

Description

It is a commonplace observation that there are layered surface rock strata. The meticulous and romantic work of geologists during this past century has shown us that these layers have systematically been sea deposited and then have risen above the sea. In some regions, the depths of these deposits have been found to be over ten kilometers. How has this come about? Consideration of this problem leads us at once to a discussion of the larger problem of the relationship between continents and ocean basins. The elementary question here is as follows: Are the configurations of oceans and continents changing or part of a permanent scheme; are the continents growing? But first let us discuss what we know about continent and ocean basin structure.

The Continents and Ocean Basins

Today we can say that the structures underlaying oceans and continents are different. The first evidence comes from geography and gravity.

First of all, the Pacific Ocean opposes in one hemisphere almost all the land waves in the opposite hemisphere. Jeffreys has pointed out that there can be no first-order terms in the gravity—second-order terms in longitude are the lowest terms—and that the center of mass must coincide with the center of the geoid (the surface of the ocean). Thus, if the rocks under the Pacific were not heavier than those under the continents, the four kilometers of Pacific Ocean water depth would represent a shift in the center of the geoid with respect to the center of mass. Since this cannot be, the average density of continental rock is less than that of oceanic rock. Thus, the Pacific Ocean acting like a giant spirit-level tells us that the continents and oceans are in mechanical equilibrium. Vening Meinesz and others have shown this in detail by submarine gravity-survey measurements at sea.

Since the war, rapid strides have been made in the exploration of the continents and oceans. Recent seismic explorations of the sea-bottom by Ewing and Press in

the Atlantic, and Raitt in the Pacific, have shown us that the ocean basins are underlain by a crust which is several kilometers in thickness and probably of lesser density than that of the mantle. Rayleigh and Love wave observations by Ewing and Press have shown us that the continental crusts are of average thickness of some 35 km and that Africa and North America are quite alike. Explosion-seismic explorations of this continent (Tuve and Tatel) reveal that the old concepts of Pratt and Airy in their simple form are not universally true, although the continents are in hydrostatic (isostatic) equilibrium.

Some great land masses, such as those of part of the Colorado Plateau and Rocky Mountain with average elevation of 6,000 feet and the Alaskan Coastal Range of 3,000 to 6,000 feet elevation, are underlain by crustal thicknesses of only 32 to 35 km compared to 30 km of a typical coastal plain such as that we are now sitting on. On the other hand, our inauspicious Appalachians have crustal depths of some 45 km.

Our present knowledge indicates then that the continental cap rock, or crust as we have long called it, is a layer of some 30 km. It is of surprising uniformity, yet it has variations in thickness apparently having no universal relationship to its superficial topographic height.

Mantle

The seismic velocity and therefore the density of mantle rock are greater than crustal rock. But is the outer mantle uniform? The velocity of mantle rock is not known too well and measurements contain variations of as much as ± 3 per cent. A 2 per cent density variation would directly affect the velocity only 1 per cent, which would escape notice. The mean value is about 8 km/sec for compression waves (mean crustal velocity is about 6.2 to 6.3 km/sec).

From detailed gravity measurement over the continent, we cannot reduce the measured fluctuations to less than about one-half by any proposed general system of adjustment of compensating masses. Thus, small but significant variations in density down to depth of several hundred kilometers could be undetected. To adjust the Colorado Plateau requires a 7 per cent average crustal density change down to 30 km, or 1 per cent down to 200 km.

In addition, we know there are deep-focus earthquakes, some at depths of 600 km. These could, for example, be associated with strength at this depth.

Thus, while we can measure transitions in the crust at 30 km, we do not know whether or not there are significant variations which extend deep into the mantle. There is, however, a bit of evidence in the form of continentwise variations in the appearance (Lehmann) of Pn seismic waves at distances as great as 1,000 km. This suggests differences in the propagation of these seismic waves in the outer mantle and consequently differences in the material itself. So, at the present moment, we are not sure that the measured seismic discontinuity at 30-km depth is coincident with a change from the crust to a completely uniform earth-mantle.

Continental Growth

The rise and fall of continental masses could be governed by crustal properties, mantle properties, transition properties between the two, or some combination. It

has been the custom to attribute all change to the crust and not to the mantle. Consider the following theories:

There are two categories of mechanical theories: large-scale world-wide phenomena and primarily local phenomena, or some combination. Then there are the theories involving mantle convection. A large-scale phenomenon is the contraction hypothesis, in which the supposed but unknown cooling of the earth has caused the earth to shrink and the crust to collapse to fit the interior. This has been suggested as the origin of folded mountains, and recently Wilson has emphasized the role of island areas in a process initiated in some manner by this shrinkage and fracture of the outer shell. Difficulties in interpretation arise because of the unknown cooling with the indefinite folding and the unknown properties of the outer mantle rock.

As for subsidence and rise, most of the known land and sea areas are floating in the heavier material below in hydrostatic equilibrium. This is called isostatic equilibrium. It is a loosely constructed hypothesis which is a model to explain the subsidence and rise of continental regions. Weathering causes the filling of shallow seas. The heavy sediment load causes this loaded subcontinent to sink. Later, earth cooling with crustal shrinkage compresses these regions, thickens them, and they float higher, causing highlands and mountains to rise. Difficulties in this hypothesis appear when numbers are put in. The differences in density of sediments and subcrustal materials can only account for 2-1/2 km of subsidence for 1 km of shallow sea-depth. Thus, geosynclines of depth of 10 km or more would have to be laid down in seas of 4-km depth or more. While this is a possible solution, it is a very special one. In some places, it does not account for what we believe did happen.

The rise of the highlands and mountains can be accounted for in some regions and not in others. One great difficulty is our lack of understanding of the amount of shortening in mountains, due to folding. The folding is three or four times greater in some ranges compared to others. Possibly, this is due to our lack of understanding of the mechanics of the folding of rocks.

A modification of this model can be made which allows for greater subsidence. If the loading of shallow seas causes a phase change of the lighter material at the base of the crust to a material of greater density, then with appropriate temperature-pressure phase characteristics, many kilometers of subsidence can occur. Later, there would be an increase of temperature due to the blanketing of the crust by the sediments and possibly due to additional flow of heat from the interior. The rock at the lower part of the crust would then be forced to convert to the less dense phase, and the crust-mantle boundary would move down and the earth surface move up.

For the present, we do not know enough about rock properties to determine whether or not such a mechanism is possible. However, the range of temperature and pressure is not outside of laboratory test. Recent theoretical considerations by MacDonald indicate that rock material could have the necessary phase-transition properties required by such a model.

In all this work, one is constantly aware of the difficulties of observation. Many times the variables are obscure, being difficult to separate. Some measurements must necessarily be made over regions so large as to obscure the small-scale

changes. Then the results obtained do not lend themselves to a unique interpretation.

Measurements in themselves are no means to an end; made without a frame of theoretical understanding, they lose their point. I believe there is much in geophysics to interest theoretical physicists. However, as in any physical science, the experiment is the decisive test of theory, not the plausibility. Thus, with imaginative theory and well-designed experiment, a better understanding of our small connection with the universe can be reached.

WALTER H. BUCHER, *Columbia University, New York, N. Y.*: **Orogenic deformation as a symptom of subcrustal changes.** The thinking of geophysicists and geologists concerning the nature of orogenesis is dominated by two diametrically opposed conceptions of the interplay between the forces at work below the earth's crust and those active within it. One sees heat transfer by convection in the earth's mantle as an essential aspect of the progressive thermal development of the earth. The drag exerted by the rising convection current as it strikes the underside of the relatively weak, inert, outermost shell of the earth, the "stereosphere" (Bucher, 1955, p. 344), is thought to set up within it tangential forces which produce compression, thickening and orogeny in the direction of movement, and tension and thinning behind it. The other, historically older, conception denies the existence, or at least the tectonic significance, of convection currents in the earth's mantle during recorded geological time. It sees orogeny as the result of failure in the relatively strong "stereosphere" placed under compression by shrinkage of the volume beneath it through secular loss of heat (chiefly by conduction).

In the last two decades, converging lines of geophysical evidence point to the second way of reasoning as nearer the truth. First, Jeffreys' quantitative appraisal of the contraction hypothesis, which includes reasonable assumptions concerning the distribution of radioactivity within the outer parts of the earth, limits the active loss of heat at the present time to a shell that extends from 100 to 700 km below the earth's surface. Second, within these same limits, deep-focus earthquakes have been recorded in the last three decades.¹ Third, Bullen, using Adams' and Williamson's equations, found that the distribution of density within the earth's mantle cannot be due solely to the effect of pressure in a homogeneous medium. Birch, using the same equations, showed that it is essentially within the same interval, that is, between 100 and perhaps down to 900 km depth, the deviation from the theoretical conditions of homogeneity, indicated by earthquake velocities, must occur. He finds that the deviation from theory reaches a maximum at about 500 km depth. According to Gutenberg and Richter, the number of deep-focus earthquakes recorded up to 1946 shows a definite secondary maximum at a depth

¹Geophysicists were inclined at first to consider deep-focus earthquakes as limited to the borders of the Pacific Ocean. Recently, two deep-focus earthquakes have been recorded from the western Mediterranean. One, from a depth provisionally given as 650 km, occurred in 37° north latitude, 3.5° west longitude, clearly related to the young alpine belt of the Betic Cordillera of Spain (U.S. Coast and Geodetic Survey, 1954). The other, assigned a depth of 450 km, from 39.6° north latitude, 13.1° east longitude, belongs to the earthquake belt of the southern Apennines and their continuation in Sicily (Bur. Centr. Internat. Séism., 1954).

of something like 600 km. The presence of a maximum in Birch's theoretical curve and the depth distribution of deep-focus earthquakes far below the base of the "stereosphere" may, of course, be merely a coincidence, but in the context of the other findings here listed it deserves attention.

Finally, plotting the release of energy through earthquakes from different zones of depth, Benioff found that, while the curves for zones below 70 km depth show a family resemblance, those for shallow earthquakes (above 70 km) bear no relationship whatever to those from greater depths. This led him to conclude that "there is no effective coupling" between what here is called the stereosphere and the greater depths. Wilson and Scheidegger were quick to point out that this contrast follows directly if tension due to shrinkage prevails below and compression above the "level of no strain."

Combined, these observations support the conclusion which Jeffreys had already drawn in 1939 that deep-focus earthquakes are the result of the formation of fractures resulting from shrinkage within the shell to which they are confined. Coulomb (1943, 1945) accepted this hypothesis and pointed out that shrinkage in a medium of the high viscosity which must prevail at the depths concerned would be accompanied by a constriction at the surface, into which the "stereosphere" would bend down, giving rise to the geosynclinal depressions on the earth's surface in which orogeny eventually takes place. Hales has recently suggested that, instead of single vast fractures, subcrustal shrinking is more likely to create "regions in which the pressure is lower than is normally the case at those depths" and in which failure would presumably be distributed in the form of numerous discrete fractures. He also thinks in terms of the "stereosphere" being forced down above these belts. In a recent address, the writer has pointed out that such a mechanism goes far to explain the basic geological features of orogenic belts.

At this occasion, the writer wishes to point to one generally neglected aspect of orogenic belts. Any hypothesis concerning the mechanics of orogenic deformation must automatically also account for the map pattern of their distribution on the earth's surface during any part of geologic time. Only that of the young folded mountain belts, as we see it on the present earth's surface, can be sufficiently defined. In its major aspect, it consists of very few, very long and narrow, more or less interrupted belts. The largest of these surrounds the Pacific Ocean. Two others, running more or less parallel to each other, separated by roughly 10° latitude, extend westward from the Himalayan and Kuenlun mountains to the Alps and the Atlas mountains. In detail, the course of these belts is characterized by lines splitting and reuniting, abrupt deflections and S-shaped turns, and especially by chains of arcs, linked in such a way that one arises from the center of curvature of its neighbor. The writer has pointed out long ago that this pattern seems incompatible with one derived from failure in a shell under compression. The question now arises whether the essential features of such a pattern would form as the result of shrinkage in a relatively thin shell. To find out, an experiment was made in which liquid castolite (with a "hastener" added) was poured into the hollow space between a wooden sphere, held in place by means of thin staples inside a transparent shell of "Plexiglas." The thickness of the empty space bore the same relation to the radius of the sphere that the hypothetical zone of shrinkage

in the earth bears to its radius. The resulting fracture pattern (Fig. 1) comprises all the features listed above as essential in the pattern of orogenic belts (see also Bucher, 1956). To the writer, this seems to be an additional argument in favor of Jeffreys' contraction hypothesis, provided it is reasonable to extrapolate from the results obtained with the six-inch sphere to the conditions to be expected on the scale of the earth.

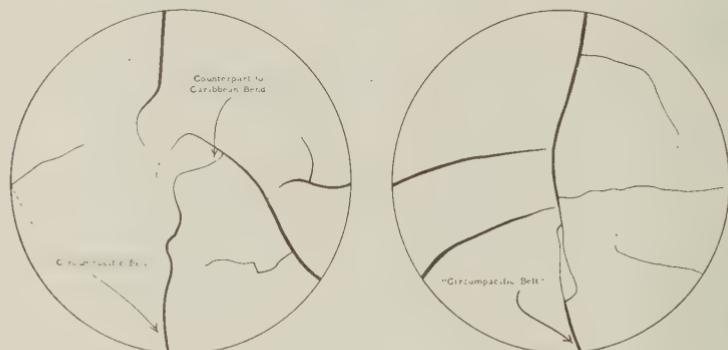


FIG. 1.

As far as the writer knows, the theoretical tools do not exist with which to answer this question. Observations on the formation of shrinkage cracks, which form in the ice-cover of lakes that are completely frozen over when the temperature drops abruptly, show that shrinkage in relatively thin layers of an elasto-viscous crystalline medium form in small numbers separated by wide distances. Such observations might well form the basis for the development of a theory of fracture through shrinkage. Such a theory would, however, be only a special case of the larger problem of the number, spacing, and pattern of fractures in solids undergoing deformation. Fractures of one kind or another stand out in the deformation of the earth's crust. The long straight lines which bound many coasts in the manner visible on an ordinary desk-globe are familiar to every geophysicist. Vening-Meinesz has used them in support of geophysical hypothesis. For the purposes of this conference, it is important to point to the urgent need of a broad theoretical attack on the whole problem of rupture in solids for the understanding of tectonic features that range in importance from microscopic dimensions to the most fundamental features on the face of the earth.

References

- Adams, L. H., and E. D. Williamson (1923); The composition of the earth's interior, Smithsonian Inst. Rep., 241-260.
- Benioff, H. (1949); Seismic evidence for the fault origin of oceanic deeps, Bull. Geol. Soc. Amer., **60**, 1837-1856.
- (1955); Seismic evidence for crustal structure and tectonic activity, Geol. Soc. Amer., S.P. 62, 61-74.
- Birch, F. (1951); Remarks on the structure of the mantle and its bearing upon the possibility of convection currents, Trans. Amer. Geophys. Union, **32**, 533-534.

- (1952); Elasticity and constitution of the earth's interior, *J. Geophys. Res.*, **57**, 227-286.
 — (1954); The earth's mantle, elasticity and constitution, *Trans. Amer. Geophys. Union*, **35**, 79-85.
 Bucher, W. H. (1933); *The deformation of the earth's crust*, Princeton, Princeton University Press.
 — (1955); Deformation in orogenic belts, *Geol. Soc. Amer., S.P.* **62**, 343-368.
 — (1956); The role of gravity in orogenesis (presidential address), *Bull. Geol. Soc. Amer.*, in press.
 Bullen, K. E. (1936); The variation of density and the ellipticities of strata of equal density within the earth, *Mon. Not. R. Astr. Soc., Geophys. Sup.*, **3**, 395-400.
 — (1940); The problem of the earth's density variation, *Bull. Seis. Soc. Amer.*, **30**, 235-250.
 — (1949); Compressibility-pressure hypothesis and the earth's interior, *Mon. Not. R. Astr. Soc., Geophys. Sup.*, **5**, 355-368.
 — (1950); An earth model based on a compressibility-pressure hypothesis, *Mon. Not. R. Astr. Soc., Geophys. Sup.*, **6**, 50-59.
 Bureau Central International de Séismologie, Bulletins d'Echange (Memorandum on Earthquake, Feb. 17, 1955).
 Coulomb, J. (1943); Une Interprétation simultanée des séismes profonds et des bandes d'anomalies de la pesanteur, Paris, C.-R. Acad. Sci., **217**, 355-356.
 — (1945); Séismes profonds et grandes anomalies de la pesanteur, *Ann. Géophys.*, **1**, 244-255.
 Gutenberg, B., and C. F. Richter (1949); *Seismicity of the earth*, Princeton, Princeton University Press.
 Jeffreys, H. (1939); Deep-focus earthquakes, *Beitr. Geophysik, Sup.*, **4**, 75-105.
 — (1952); *The earth*, Cambridge, University Press, 3rd ed.
 Hales, A. L. (1953); The thermal contraction theory of mountain building, *Mon. Not. R. Astr. Soc., Geophys. Sup.*, **6**, 458-466.
 — (1953); The thermal contraction theory of mountain building (second paper), *Mon. Not. R. Astr. Soc., Geophys. Sup.*, **6**, 486-493.
 Scheidegger, A. E., and J. T. Wilson (1950); An investigation into possible methods of failure of the earth, *Geol. Assoc. Canada*, **3**, 167-190.
 U.S. Coast and Geodetic Survey (1954); Preliminary determination of epicenters, Card 59-54.
 Vening-Meinesz, F. A. (1947); Shear patterns of the earth's crust, *Trans. Amer. Geophys. Union*, **28**, 1-61.
 Wilson, J. T. (1949); An extension of Lake's hypothesis concerning mountain and island arcs, *Nature*, **164**, 147-148.
 — (1950); An analysis of the pattern and possible cause of young mountain ranges and island arcs, *Geol. Assoc. Canada*, **3**, 141-166.
 — (1954); The development and structure of the crust, in "The solar system, the earth as a planet," G. P. Kuiper (Ed.), Chicago, University of Chicago Press, 138-214.

FRANK PRESS, *California Institute of Technology, Pasadena, California: Some new trends in seismology.** As a result of some 50 years of effort, seismologists have provided us with fairly good notions of the variation of elastic parameters with depth in the earth. The silicic crust has been found to extend to a depth of 35 km beneath continents and 11 km beneath the sea-surface. The boundary between the mantle and fluid core has been located, and indications have been found of a solid inner core. These results have been achieved primarily by study of travel times of seismic body waves generated in earthquakes and explosions.

With the availability of this knowledge of basic earth structure, our attention

*Contribution No. 769, Division of Geological Sciences, California Institute of Technology, Pasadena, California.

is turning to finer details. Such problems as the nature of crustal structure in orogenic belts and continental margins, or the detection of elastic differences between the mantle under oceans from that under continents, are attracting the attention of seismologists. Better precision in travel-time curves is being sought to enable further progress in the delineation of the low-velocity layer and the study of the nature of the mantle material.

To illustrate some of the new approaches in seismology, a few examples are given.

L_g phase—The *L_g* phase is a short-period surface wave, limited to propagation in the continental crust. It has been used to establish the extent of continental masses and to demonstrate uniformity in the shear velocity of materials of the earth's crust. A detailed theory for the mechanism of propagation of this phase is not yet available.

Phase velocity of surface waves—Phase velocities of Rayleigh waves are being measured with sufficient precision to show the effect of local variations in thickness of the earth's crust. This has been accomplished by use of Rayleigh waves which have traversed long oceanic paths. The resulting separation in time of the harmonic components of the wave train is sufficient to raise the accuracy of phase-velocity determination to the necessary level. Application of this method in California has shown the manner of crustal thickening from the continental margin to the Sierra Nevadas.

P_a and S_a waves—These are compressional and shear waves guided by a channel in the upper part of the mantle. They serve to determine the velocity of body waves in the channel and may provide a means for detecting differences in the mantle under continents and oceans.

Mantle surface waves—Both Rayleigh waves and SH waves (G waves) have been observed from certain large earthquakes. These waves are affected primarily by the variation of shear velocity with depth in the mantle. An outstanding problem is the absence of dispersion in the G wave in contrast to the pronounced dispersion of the Rayleigh waves. A theory involving a low-velocity layer in the mantle and the effect of curvature is probably needed to account for this phenomenon. The absorption of these waves leads to useful estimates of the solid friction parameters of the mantle.

Other important new developments include the study of strain release of earthquakes, the determination of motion at the earthquake fault from a study of seismograms, the use of seismic models as analogue computers, and the development of the seismographs with extended sensitivity in the long-period range.

L. B. SLICHTER, *Institute of Geophysics, University of California, Los Angeles, California*: **Theoretical seismology.** Seismology provides essentially the only means for obtaining information about the detailed structure of the earth's deep interior, and the interpretation procedures used are still those of geometrical optics, developed about 50 years ago. Theoretically, at least, the use of interpretation methods based upon elastic theory, in which more than the first arrivals are utilized, enables the determination of the variation of density with depth, as well as that of the two wave velocities. At present, elastic theories for seismic

interpretations are primitive and unsatisfactory, and thus the creation of better analytical tools of interpretation is a challenging objective for theoretical seismologists. Pending the development of such tools, it is suggested that valuable evidence concerning the validity of present ideas of the interior structure, and regarding the permissible range of variation for the values of the elastic and density parameters in the interior, could be obtained by setting up the pertinent elastic equations for a number of different earth models, solving these equations on an electronic computer, and comparing the synthetic seismograms so derived with those actually observed.

B. GUTENBERG, *California Institute of Technology, Pasadena, California:*
Structure of earth's interior. Improved quality and increased quantity of observations connected with geophysical processes in the earth's interior may require inclusion of heretofore neglected second-order terms in the theory. One example is the necessity to consider the energy gradient along the wave front of seismic waves, which usually is taken as zero, but which frequently cannot be neglected in calculations of the energy flux in the neighborhood of discontinuities or through the newly discovered low-velocity layers. Other instances where terms of higher order are needed occur in the investigation of non-elastic processes, such as damping of elastic waves. The relatively heavy damping of the "free nutation" of the earth's axis of rotation found in some discussions of the problem seems to result from use of oversimplified assumptions, especially from disregarding the energy supply from annually shifting air-masses, water, etc. The combination of the 12-month period of these energy sources with the free Chandler period of 14 months leads to an increase and decrease of the polar motion, with a period of about seven years, which has been used to calculate the damping without consideration of the energy supply.

MAURICE EWING, *Lamont Geological Observatory, Columbia University, Palisades, N. Y.:* **Periods of seismic waves and mantle structure.** Many earthquakes send strong signals in the period range of one to three seconds in the L_g phase along purely continental paths. In general, the periods in the P phase from these same shocks are considerably longer, while that of the S phase is in many cases 20 or 30 seconds.

From oceanic epicenters, T phases, with periods 1/2 to 2 seconds, are commonly recorded when the propagation path is purely oceanic, but P and S phases again are much longer in period.

The presence of short periods in T and L_g proves that some defect of transmission, more pronounced for shear waves than for compressional waves, is responsible for the absence of the short periods in P and S. It is suggested that numerous bodies of molten basaltic magma are present in the upper several hundred kilometers of the mantle of most of the earth. (The implications of this hypothesis for the propagation of the G phase, composed of long period, non-dispersed, horizontally polarized shear waves were discussed.)

Over certain oceanic paths from the West Indies to Bermuda and Palisades, remarkably short periods are commonly found in P and S, proving that the upper

mantle in this area has excellent elastic properties at periods of 1/3 to 1 cycle per second.

J. VERHOOGEN, *University of California, Berkeley, California:* **Heat sources in the earth.** An outstanding geophysical problem is to determine what sources of energy exist within the earth, and how they maintain geological processes such as volcanic activity and mountain-making. It appears that the energy involved in such processes is but a small fraction of the total heat carried by conduction to the earth's surface. The first step is thus to find a distribution of heat sources within the earth that will account for the main surface heat flow.

The following considerations are relevant:

- (1) There is no direct evidence as to whether the earth is in a steady thermal state or otherwise.
- (2) Because of the earth's size, surface heat flow cannot give information on heat sources at depths greater than about one-tenth of its radius.
- (3) The temperature in the mantle remains below the melting-point except locally and intermittently.
- (4) In spite of surface differences, the average temperature must be very nearly constant along level surfaces in the mantle. There is no evidence that the average temperature of the mantle is different in oceanic and continental sectors.
- (5) The distribution of radioactive heat sources follows a broad geochemical pattern. For instance, there is more radioactive material in granite than in peridotites.

To date, there is no generally accepted model of the earth that will account for its surface heat flow, let alone for the temperature perturbations implied in volcanic phenomena or mountain-making.

Progress may be sought along the following lines:

(a) *Mechanism of heat transfer*—Although the relevant solutions of the equation of heat conduction are well known, the numerical value of the thermal conductivity in the mantle is not. This involves a difficult problem in solid-state physics. The possibility must also be considered that heat may be transferred by convection. An essential difficulty in the convection problem is that of choosing adequate stress-rate of strain relations, as there is practically no independent evidence on the rheological properties of the mantle. The problem is a fascinating one, because of possible application to tectonophysics.

(b) *Actual temperature distribution within the earth*—Much could be learned regarding heat sources within the earth if the temperature distribution at the present time were known. The temperature at any depth could in theory be derived from measurements of physical properties which depend on temperature. The electrical conductivity, for instance, is very sensitive to temperature. Unfortunately, it is also sensitive to other factors, such as the ratio of metal to silicate in the mantle and their geometric relationships. The velocities of longitudinal and transverse elastic waves, which are known at all depths with sufficient accuracy, are also functions of the temperature. Present theoretical knowledge on the behavior of solids at extreme pressure is, however, still inadequate to disentangle temperature effects from those of pressure, chemical composition, and crystal structure. Pend-

ing a better knowledge of the chemical composition of the core, temperature determinations based on assumed phase transitions (for example, melting at the inner-core boundary) rest on an insecure basis. The question of the chemical composition of the core is particularly relevant with regard to possible heat sources and the maintenance of the convective motion suggested by present theories of the earth's magnetic field. Theories of the origin of the earth have an important bearing on the matter.

W. A. HEISKANEN, Ohio State University and International Isostatic Institute, Columbus, Ohio: **Gravity and geodesy.** The main task of geodesy is to determine the size and shape of the earth and to furnish the cartographic workers with accurate and reliable control points. The difficulty of geodesy is now the fact that the mathematical surface (reference ellipsoid) along which we compute the co-ordinates beginning from the initial point of the geodetic systems, and the sea-level (geoid), to which our observations are referred, are different surfaces. Consequently, we ought to know the distance N and the components ξ and η of the tilt between these two surfaces. These quantities N , ξ , and η we do not know, in general.

The only method which can give them at any arbitrary point, the oceans included, is the gravimetric method, also called physical geodesy. Not only N , ξ , and η , but also the gravity anomalies Δ_a (observed minus theoretical value), are caused by the disturbing visible and invisible mass anomalies Δ_m of the earth. Δ_a can be measured; N , ξ , η , which determine the shape of the geoid, can be computed in using Stokes' formula (1849) and Vening Meinesz' formula (1928). Δ_a must be known in the neighborhood of the computation point quite accurately and in broad lines all over the world. When we know N , ξ , and η at the initial points of different geodetic systems, it is easy to convert these geodetic systems to the World Geodetic System along the reference ellipsoid. Also, every astronomic point at which ξ and η have been computed gravimetrically is a useful control point. In addition, the dimensions of the earth reference ellipsoid can best be checked by the cooperation of the gravimetric and arc-measuring methods.

These are the main aims of the world-wide gravity program, which the author had the honor to establish in 1950 at Ohio State University. Since the isostatic gravity anomalies are most representative, so that one single isostatic anomaly can, if needed, represent even an area of about $2.6^\circ \times 2.6^\circ$, or 32,000 square miles, this reduction has to be used. The value 30 km for the normal thickness T of the earth's crust is most probable and will be applied. Table 1 shows why the value $T = 30$ km has been used.

The rapid and accurate gravimeters, the possibility of measuring the gravity also of the oceans, the enthusiasms of F. A. Vening Meinesz, M. Ewing, and L. Worzel in carrying out the gravity survey of the oceans, and of G. P. Woppard and his group in connecting the gravity base-stations of the world to the same Potsdam system are the prerequisites of this program.

Thirty-one countries, including Australia, New Zealand, India, Japan, Union of South Africa, hundreds of scientists, and several oil companies cooperate with us. Most effective help has been given by Vening Meinesz, T. J. Kukkamäki, R. A. Hirvonen, P. Lejay, Walter Lambert, Worzel, and Woppard.

TABLE 1—*The gravity anomalies Δ_g^* as function of the observation height H^{**}*
($T = 0$ means the free air reduction, $T = \infty$ the Bouguer reduction)

Norway (Heiskanen)		Ferghana (Erola)
$T =$	$0 \text{ km}; \Delta g = - 6 + 38 \times H$	$T = 0 \text{ km}; \Delta g = - 138 + 16 \times H$
=	$40 \text{ km}; \Delta g = + 20 - 8 \times H$	= $20 \text{ km}; \Delta g = - 71 + 14 \times H$
=	$60 \text{ km}; \Delta g = + 21 - 20 \times H$	= $30 \text{ km}; \Delta g = - 59 + 7 \times H$
=	$80 \text{ km}; \Delta g = + 18 - 28 \times H$	= $40 \text{ km}; \Delta g = - 51 - 1 \times H$
=	$100 \text{ km}; \Delta g = + 14 - 35 \times H$	= $60 \text{ km}; \Delta g = - 38 - 12 \times H$
=	$\infty \text{ km}; \Delta g = - 3 - 80 \times H$	= $80 \text{ km}; \Delta g = - 31 - 20 \times H$
		= $100 \text{ km}; \Delta g = - 26 - 27 \times H$
		= $\infty \text{ km}; \Delta g = - 138 - 87 \times H$
Central Alps (Holopainen)		North Italy (Morelli)
$T =$	$0 \text{ km}; \Delta g = - 137 + 60 \times H$	$T = 0 \text{ km}; \Delta g = - 58 + 39 \times H$
=	$20 \text{ km}; \Delta g = - 1 - 2 \times H$	= $20 \text{ km}; \Delta g = + 38 + 9 \times H$
=	$30 \text{ km}; \Delta g = + 1 - 11 \times H$	= $30 \text{ km}; \Delta g = + 40 - 1 \times H$
=	$40 \text{ km}; \Delta g = 0 - 17 \times H$	= $40 \text{ km}; \Delta g = + 40 - 8 \times H$
=	$60 \text{ km}; \Delta g = - 6 - 23 \times H$	= $60 \text{ km}; \Delta g = + 37 - 18 \times H$
=	$\infty \text{ km}; \Delta g = - 85 - 39 \times H$	= $\infty \text{ km}; \Delta g = - 36 - 43 \times H$
West Carpathians (Tanni)		
$T =$	$0 \text{ km}; \Delta g = + 13 + 14 \times H$	
=	$30 \text{ km}; \Delta g = + 28 + 0 \times H$	
=	$60 \text{ km}; \Delta g = + 34 - 23 \times H$	
=	$\infty \text{ km}; \Delta g = + 8 - 53 \times H$	

*According to free air, Bouguer and isostatic Airy-Heiskanen reduction; T is the normal thickness of the earth's crust.

**Unit of $\Delta_g = 1 \text{ mgal}$, of $H = 1000 \text{ m}$.

Some thousands of N -values might be computed in a few months. The accuracy of the N -values is about 7 to 10 m, the accuracy of ξ and η about 0.8 to 1.5 sec. When additional observations are available, higher accuracy will be obtained.

The world-wide gravity program is sponsored by the Cambridge Research Center of the Air Force and is carried out in the Mapping and Charting Research Laboratory of the Ohio State University Research Foundation. This program is a natural continuation of the studies of the author with his students, carried out in Finland since 1924.

The method to determine gravimetrically the thickness of the earth's crust is simple. When the different gravity anomalies are written as function of the height of the gravity stations, a clear dependence on the elevation can be seen. As Table 1 shows, the elevation term is in the free air anomalies positive and in the Bouguer anomalies strongly negative. Using the criterium that the isostatic reduction suits best that which causes the elevation term to disappear, we obtain for the normal thickness of the earth's crust in Norway 32 km, in the Ferghana area 38 km, under the Central Alps about 20 km, under the West Carpathians 30 km, and in Northern Italy 29 km. Since the used density difference between Sima and Sial layers is 0.6, the real thickness of the Sial layer (earth's crust) is 5.5 km more for every 1,000-meter elevation, as well as 3.8 km less for every 1,000-meter depth.

Figure 1 shows what kind of difficulties the irregular shape of the geoid can cause in determining the dimensions of the earth.

Figure 2 shows that the gravity anomalies, as well as the distances and tilt

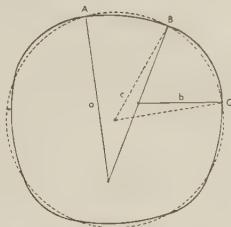


FIG. 1—Irregular shape of the sea-level earth, or geoid (solid curve) causes errors in measuring the radius of the planet's theoretical figure (broken ellipse). Where the geoid is flatter than the reference ellipsoid, as between A and B, verticals at the end points will meet at a point more distant than the true center, thus giving the radius a , which is too large. Where the geoid is more sharply curved than the reference figure, as between B and C, the verticals intersect before the center, thus giving radius b , which is not large enough.

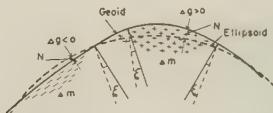


FIG. 2—The invisible mass anomalies Δ_m (surplus or deficiencies) bring about the gravity anomalies Δ_g , undulations N of the geoid, and deflections of the vertical ξ . Δ_g can be observed; N and ξ can be computed. This is the fundamental idea of the world-wide gravity program of the Columbus group.

between the reference ellipsoid and geoid, are brought about by the disturbing masses. The gravity anomalies can be observed; the distance and tilt between the geoid and ellipsoid can be computed.

GEORGE P. WOOLLARD, *University of Wisconsin, Madison, Wisconsin*: **Geological geophysical problems.** While there are many problems of a purely geophysical nature that would benefit through more rigorous theoretical studies, there is a rather extensive list of geological problems posed by both geological and geophysical observations that require study. Some of these problems, which may appear to be of a minor nature to the physicist and mathematician, such as what type of rock should be associated with seismic velocity values, are quite fundamental to both the geologist and geochemist. Others are related to the ambiguity of interpretation of some geophysical data such as those obtained with both gravitational and magnetic measurements. Some are related to a lack of knowledge concerning physical constants within the earth. Others reflect the lack of knowledge concerning earth tectonic processes, such as what factors govern cyclic periods of mountain building on a world-wide scale.

In the following list, some of the more pertinent unsolved or only partially solved geophysical problems having especial geologic significance are tabulated.

No attempt has been made to arrange them in order of importance, since manifestly what would be of paramount importance to one investigator might be of only passing interest to another. However, the list has been subdivided into three categories, as follows: Those related to the earth as a whole, those more or less peculiar to the continents, and those related to the ocean basins.

Some Unsolved Problems in Geology Related to Geophysics

A—*The earth as a whole*

1. The origin of the continental blocks and ocean basins
2. The permanence of the continental blocks and ocean basins
3. The migration of the continental blocks and their possible growth
4. The expansion or contraction of the earth and its tectonic significance on
(a) the pattern of interconnected mountain ranges on the continents, and
island arcs and submarine mountains in the ocean; (b) the origin of mountains and island arcs; and (c) the pattern of world earthquake belts
5. The elastic and plastic behavior of the crust under stress
6. The cause of cyclic epeirogenetic movement (uplift) and orogenic (mountain building) activity
7. Factors controlling the unidirectional movements of crustal units, as along the Pacific coast of California
8. Significance of regional areas out of isostatic equilibrium
9. The origin of the earth's magnetic field
10. The migration of the magnetic poles and its relation to the axis of rotation of the earth
11. Significance of areas having abnormal magnetic fields and their relation to other geophysical fields
12. Induced magnetism *vs* permanent magnetism in sediments
13. The explanation for reversals in magnetic polarity observed in sediments
14. Relationship of sunspot activity and earth currents to rock magnetism, if any
15. Causes for wave guides (sound channels) in the crust and mantle, and why there is a difference in the relations on the continents and oceans
16. Age relationships of rock types on continents and oceans
17. Why the heat flow observed on both the continents and in the oceans appears to be the same
18. Factors giving apparently uniform paleoclimates rather than zoned climates as at present

B—*The ocean basins*

1. Distribution of sediments, their thickness, age, and magnetic polarization
2. Density currents, their extent, and importance as erosional and depositional agents
3. Explanation for extreme variations in bottom topography in the open ocean
4. Uniformity of crustal structure in open ocean

5. Significance of Andesite line
6. Significance of structural geologic pattern of island arcs and their relation to anomalous gravitational and seismic phenomena, particularly deep focus earthquakes
7. Significance of gravity anomaly variations in open ocean
8. Origin of submarine canyons
9. Significance of flat-topped Guyots at mid-depths
10. Significance of differences in continental shelf areas (Pacific *vs* Atlantic on North America)
11. Variations in near-surface structure under continental shelves
12. Subsidence of oceanic islands and relation to underlying crustal structure

C—The continents

1. Age variations of rocks comprising the crystalline nuclei of continent
2. Origin and distribution of igneous rocks (both acid and basic)
3. Formation of mobile belts (lenticular areas of subsidence) in contrast to centers of uplift or subsidence
4. Maximum thickness of sediments possible without crustal failure
5. Mechanism of failure in subsiding mobile belts to give mountains
6. Degree to which granitization is a major factor in the formation of granites
7. Nature of crustal boundaries between continents and oceans
8. Mechanics of short-term period epeirogenetic changes in continental relief
9. Variations in crustal structure with different geologic provinces
10. Mode of subsurface compensation for variations in surface relief where isostasy prevails
11. Explanation for areas out of isostatic equilibrium on continent, particularly grabens and horsts

From an inspection of the above, it is seen that the problems can be separated into the following three categories:

- (1) Those in large part related to the absence of data or for which there are few data
- (2) Those for which there are a fair accumulation of geophysical observational data, but whose interpretation leads to conflicting geologic conclusions
- (3) Those for which there are a fair amount of geophysical observational data, but whose geologic interpretation is handicapped by a lack of analytical and theoretical study

Most of the problems listed fall into the first and second groups. Geological geophysics is still in the stage occupied by meteorology not so long ago; namely, that the theory best fitting the observational data is constantly having to be modified as new observational data become available. A complicating factor is that many of the problems listed are intimately interrelated, and any solution proposed for one pertains at least in part for several others. For example, any model of crustal structure as deduced from earthquake travel-times not only must

be in accordance with the indications of surface-blast studies and the dispersion of Rayleigh waves, but also be in accord with gravitational anomalies, density stratification of rocks with depth, and concepts of geochemistry and physical chemistry concerning the petrologic composition of the crust, and the effects on density and seismic-wave propagation velocity of phase changes because of temperature and pressure conditions at depth.

In this respect, the problem is somewhat analogous to that of the interrelated studies of sunspots, the earth's magnetic field, the ionosphere, radio sky-wave transmission, cosmic-ray activity, the aurora, and telluric (electrical) currents in the ground and their relation to surficial geology. However, in contrast to ionospheric studies which are now being advanced at a rapid rate, the crustal studies are handicapped by few data, a slow rate of acquisition entailing much labor and effort, and results not presenting a single simple solution. For this reason, the need for theoretical studies is probably greater in this field than in other branches of geophysics.

H. S. YODER, *Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.*: **Thermodynamic problems in petrology.** Many of the problems now confronting the petrologist require the techniques of skilled theoretical and experimental thermodynamicists. Equations of state are needed for rock-forming materials under the extreme conditions (10,000 bars pressure and temperatures locally up to 1600°C) thought to exist at depths as great as the Mohorovičić discontinuity. The ideal gas laws and the relations derived from them have been shown by direct experiment not to be applicable to the non-ideal naturally occurring solids and fluids. Several examples of the thermodynamic problems met by the experimental petrologist follow.

Definition of the volume of the phases in a one-component system at a transition or melting point is one of the problems. Large discrepancies have been found between the calculated and the measured volume changes for the α - β quartz transition and the melting of diopside. Volume changes are particularly significant in the phase changes of rocks at depth; they may play an important role in mountain building and extrusion of lava.

Experimental data have been collected on some 200 anhydrous silicate systems, and the thermodynamic analysis of these systems would yield valuable information on activities, heats of mixing, and entropy of mixing. Systems not now amenable to experiment could then be outlined by calculation with such information and other thermochemical data.

The few thermochemical data now being obtained on rock-forming materials are, unfortunately, not of sufficient accuracy to solve the problems of immediate interest to the petrologist. In solution calorimetry, for example, a completely new approach is required for the hydrous minerals and relatively insoluble silicates.

The general relations of phases in a system involving an anhydrous solid and a volatile (for example, diopside-water) have been outlined qualitatively, but the exact functions are not known. Small portions of the phase boundary curves have been determined; however, theories are needed to guide future experiments under the extreme conditions.

The thermodynamic relations for the decomposition of a hydrous mineral are only crudely known. For example, large discrepancies were found between the enthalpy calculated from the integrated Clapeyron equation, $\Delta H = -RT\ln P_{H_2O} + C$, and the more direct relation $\Delta H = T\Delta VdP/dT$, even though the assumptions in each case appear to be satisfied for pressures less than 1,000 bars. For the decomposition of muscovite, the methods yield an enthalpy of 31.6 kcal/mol and 14.2 kcal/mol, respectively.

Another problem involves one of the most important concepts in geothermometry: the use of unmixing relations in the subsolidus region of mineral systems involving solid solution. In one case, which has been outlined experimentally, muscovite-paragonite, the unmixing curve can be computed with some accuracy if given one set of data on the curve. The petrologist would like to be able to calculate these curves without the aid of experimental data, because equilibrium is very difficult to obtain in the subsolidus region.

There are a large number of thermodynamic problems in areas in which no successful experiments have been made. The behavior of reactions when the pressure of the participating volatile is less than the total pressure is of extreme interest to the petrologist. He would also like to know the effects of shear on a heterogeneous reaction and to learn of methods for estimating the chemical potential of a phase in an open system.

GORDON J. F. MACDONALD, *Massachusetts Institute of Technology, Cambridge, Massachusetts*: **Equations of state of solids in the earth.** One of the primary aims of theoretical research in thermodynamics of rocks and rock-forming minerals is to establish equations of state that will provide an adequate basis for calculating the properties of solids at conditions of temperature and pressure that cannot as yet be reached by direct experiment. The equations of state can then be used to interpret geophysical data relative to the deep earth.

The thermodynamic properties of matter can be described in terms of a mechanical and a thermal equation of state. These equations can be written in the integral form for one-component, constant-mass systems, as

$$P = P(VT)$$

$$S = S(VT)$$

where S is the entropy of the system. The mechanical and thermal equations are not independent, but are related by

$$\left(\frac{\partial S}{\partial P}\right)_V = -\left(\frac{\partial V}{\partial T}\right)_P = V\alpha$$

where α is the coefficient of thermal expansion.

The present state of theories of equation of state is such that the variation of entropy with temperature and the variation of pressure with volume can be adequately described. The variation of volume with temperature or the variation of entropy with pressure is much less well known, as there is as yet no satisfactory theory for thermal expansion of solids. In terms of the differential coefficients heat capacity, C_v , and incompressibility, K , the variation of heat capacity with

volume and the variation of incompressibility with temperature cannot at present be treated theoretically. Since both pressure and temperature change within the earth, we need the coefficients $(\partial C_v / \partial V)_T$ and $(\partial K / \partial T)_V$ as a function of volume and temperature to treat the materials within the deep earth.

The present paper will review the theory of variation of heat capacity with temperature with special reference to the problems in complex solids. The state of the theory of the variation of pressure with volume is considered. The importance of developing a theory of thermal expansion is pointed out, since on this depends the proper evaluation of the variation of heat capacity with volume and incompressibility with temperature.

Thermal Equation of State

In the theory of heat capacity at constant volume (see Slater, 1939, Born and Huang, 1954), a solid is approximated by an ensemble of simple harmonic oscillators vibrating with frequencies ν_γ . The principal problem in the theory is then to determine the number of frequencies falling in a particular interval of frequency (ν , $\nu + \Delta\nu$). In the Einstein theory of heat capacity of monoatomic isotropic solids, it is assumed that all the vibrational frequencies ν_γ are equal. In the Debye model of a solid, the frequency spectrum is given by

$$\begin{aligned} f(\nu) &= c\nu^2 \quad \text{for } \nu < \nu_{\max} \\ &= 0 \quad \text{for } \nu > \nu_{\max} \end{aligned}$$

Both of these theories are distinguished by the introduction of a characteristic temperature for the solid. In the Einstein model, this temperature is given by $\theta_E = h\nu/k$, where ν is the frequency of vibration of the atoms. In the Debye model, the characteristic temperature is given by the analogous expression $\theta_D = h\nu_m/k$, where ν_m is the maximum frequency of vibration. In both theories, the heat capacity varies markedly with temperature below the characteristic temperature and varies much less above the characteristic temperature.

In extending such theories to complex solids, consideration should be given to the relation of the frequency spectrum to the atomic structure of the solid. In geophysics, we are primarily interested in silicates, which make up a dominant part of the crust of the earth and which presumably are important constituents of at least the upper part of the mantle of the earth. The building block of silicates is a unit composed of a central silicon atom surrounded by four oxygen atoms in a tetrahedral arrangement. These silicon-oxygen tetrahedra are joined together either by sharing oxygen atoms between silicones or by joining tetrahedra or groups of tetrahedra together by atoms such as iron, calcium, magnesium, sodium, etc. The vast array of silicate minerals represents differing arrangements of silicon-oxygen tetrahedra and metallic atoms. The actual geometrical arrangements are for the most part extremely complex and as a result detailed calculations of the frequency spectrum are exceedingly difficult. For many purposes, a good approximation to the silicate structure is obtained by considering silicates as composed of silicon-oxygen tetrahedra, with the oxygens in more or less close packing, and metallic atoms occupying the interstices between the oxygen atoms.

An approximation to the frequency spectrum in silicates is obtained from measurements of the infrared absorption spectrum of minerals. These measurements (Keller, Spotts, and Biggs, 1952) show that absorption bands are spread over a considerable range of frequencies, but that the spectrum can be divided approximately into two parts, a high frequency part due principally to the internal vibrations of the silicon-oxygen tetrahedra, and a lower frequency part resulting from the vibrations of the metallic atoms and of the silicon tetrahedra as units. We can term the part of the spectrum resulting from the internal silicon-oxygen tetrahedra vibrations the optical branch of the spectrum, and the lower frequency portion the acoustic branch of the spectrum. The Debye theory strictly applies only to the acoustic part of the spectrum, but the theory can approximate the more complex frequency spectrum provided that the maximum frequency ν_m adequately weights the optical branch of the spectrum.

The general form of the frequency spectrum in silicates is illustrated by the temperature dependence of the Debye temperature θ_D . In Table I, the Debye

TABLE 1—"Low" and "high" temperatures
(Debye temperature for silicates and oxides)

Mineral	θ_D at 50°K	θ_D at 298°K
	°K	°K
Quartz, SiO_2	500	1020
Albite, $\text{NaAlSi}_3\text{O}_8$	450	950
Leucite, KAlSi_3O_6	400	900
Forsterite, Mg_2SiO_4	640	875
Corundum, Al_2O_3	865	970

temperature determined by the heat capacity of the mineral at 50°K is compared with the Debye temperature determined by the 298°K heat capacity. The Debye temperature at 298°K for silicates is greater than the Debye parameter at low temperature. This results from the fact that at a low temperature the internal tetrahedral vibrations are not excited and these vibrations contribute little to the heat capacity at low temperatures. This effect is particularly marked in minerals such as quartz and feldspar, made up dominantly of the silicon tetrahedra.

In the Debye theory, the Debye temperature can be expressed in terms of the velocity of the longitudinal and transverse waves in the solid. A Debye temperature as function of depth within the earth can thus be determined from the observed seismic velocities. It is of interest to investigate what the Debye temperature obtained from elastic data refers to in complex solids.

Two elastic constants of an isotropic solid determine the Debye temperature for the solid. Alternatively, the Debye temperature plus one constant, compressibility, would determine the other elastic constant, rigidity. Using the Debye theory and θ_D determined by 50°K specific heats, good agreement is obtained between observed and calculated rigidities, as is illustrated in Table 2.

No agreement between calculated and observed elastic properties is obtained

TABLE 2—*Comparison of calculated and measured rigidities of minerals*

Mineral	Calculated μ	Observed μ
	<i>bars</i> $\times 10^{-5}$	<i>bars</i> $\times 10^{-5}$
Olivine, $(\text{MgFe})_2\text{SiO}_4$	5.5	4.8 to 6.2
Albite, $\text{NaAlSi}_3\text{O}_8$	2.6	2.8
Anhydrite, CaSO_4	2.8	2.8
Calcite, CaCO_3	1.5	1.1 to 2.3

if the 298°K values of θ_D are used. The disagreement is large, since the rigidity depends on the square of θ_D .

The interpretation of the elastic properties in terms of the Debye theory leads to the conclusion that the elastic properties of solids can give information as to the acoustic part of the spectrum, but at least for low pressures the vibrations in the optical region are not represented by the elastic properties. The conclusion is important in interpreting the Debye temperature of material within the earth derived from seismic velocities. The seismic velocities should give information as to the acoustic part of the frequency spectrum. The acoustic part of the spectrum by itself does not determine the thermal properties of the solid and therefore the seismic data do not define the thermal properties of materials within the earth. Attempts have been made by Verhoogen (1951, 1955), Jacobs (1953), Uffen (1952), Valle (1952), and Miki (1954) to obtain the thermal properties of the earth from seismic data. None of these attempts has taken proper account of the limitations of the Debye theory in dealing with complex solids. Conclusions derived from these treatments as to the temperature within the earth, the melting point gradient, and the adiabatic gradient should be viewed with great caution. These considerations in addition emphasize our ignorance as to the temperature and thermal properties of the deep earth.

Mechanical Equation of State

Little progress has been made in developing mechanical equations of state on a molecular model. Most molecular theories of cohesion are characterized by the introduction of several empirical parameters. Löwdin (1948) has given an approximate quantum-mechanical theory of simple salts, in which no experimental parameters are introduced, except for atomic constants. However, the extension of this theory to complex oxides and silicates is difficult. The properties of solids at high pressures and constant temperature can be treated successfully by Murnaghan's (1937, 1951) theory of finite strain. This theory is thermodynamic in character and involves the expansion of the Helmholtz free energy at constant temperature in terms of the strain invariants, where the higher-order terms in the strain are not neglected.

A major question in applying the theory to geophysical problems is the number of terms in the series, or alternatively, the number of empirical constants that must be used to describe the deformations that might be expected within the earth. Birch (1952), in an exceedingly thorough analysis of Bridgman's experi-

mental data, finds that deformations in which the original volume is halved can be described by the finite strain theory with the introduction of only one empirical parameter. Duvall and Zwolinsky (1955) have shown that Walsh and Christian's (1955) shock-wave measurements on metals at pressures on the order of several hundred thousand bars can be treated by the Murnaghan theory with two empirical constants. So far, the theory has been thoroughly tested with compressible metals, but because of the thermodynamic nature of the theory there is no reason to doubt its applicability to the relatively incompressible materials that make up the earth.

The major problem in applying Murnaghan's equation of state to materials of the earth lies in the evaluation of the effect of temperature on incompressibility or other elastic constants. Few experimental data are available on the temperature coefficient of incompressibility, and, since the coefficient is a function of the coefficient of thermal expansion, little progress has been made in evaluating the temperature dependence of the incompressibility.

References

- Birch, F. (1952); Elasticity and constitution of the earth's interior, *J. Geophys. Res.*, **57**, 227–286.
- Born, M., and K. Huang (1954); *Dynamical theory of crystal lattices*, Oxford, University Press.
- Duvall, G. E., and B. J. Zwolinsky (1955); Entropic equations of state and their application to shock wave phenomena in solids, *J. Acoust. Soc. Amer.*, **27**, 1054–1058.
- Jacobs, J. A. (1953); Temperature-pressure hypothesis and the earth's interior, *Can. J. Phys.*, **31**, 370–376.
- Keller, W. D., J. H. Spotts, and D. L. Biggs (1952); Infrared spectra of rock-forming minerals, *Amer. J. Sci.*, **250**, 453–471.
- Löwdin, P. (1948); A theoretical investigation into some properties of ionic crystals, Ph.D. thesis, Upsala, Sweden.
- Miki, H. (1954); Temperature distribution within the earth, *J. Phys. Earth*, **2**, 1–3.
- Murnaghan, F. D. (1937); Finite deformations of an elastic solid, *Amer. J. Math.*, **59**, 235–260.
- (1951); Finite deformation of an elastic solid, New York, J. Wiley and Sons, Inc.
- Slater, J. C. (1939); *Introduction to chemical physics*, New York, McGraw-Hill Book Co., Inc.
- Uffen, R. J. (1952); A method for estimating the melting point gradient in the earth's mantle, *Trans. Amer. Geophys. Union*, **33**, 883–896.
- Valle, P. E. (1952); Una relazione diretta fra la velocità delle onde elastiche e la densità nell'interno della terra, *Ann. Geofis.*, **5**, 417–431.
- Verhoogen, J. (1951); The adiabatic gradient in the mantle, *Trans. Amer. Geophys. Union*, **32**, 41–44.
- (1955); Thermal expansion of solids and the temperature at the boundary of the earth's core, *Trans. Amer. Geophys. Union*, **36**, 866–874.
- Walsh, J. M., and R. H. Christian (1955); Equation of state of metals from shock wave measurements, *Phys. Rev.*, **97**, 1544–1556.

2:00—5:00 P.M.

L. V. Berkner, Chairman

L. T. ALDRICH, Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.: Radioactive age measurements. Recently developed chemical techniques and stable isotope dilution have made possible quantitative determinations of mineral ages using the rare isotope K^{40} and the

long-lived isotope Rb⁸⁷. From ratios radiogenic A⁴⁰/K⁴⁰ and radiogenic Sr⁸⁷/Rb⁸⁷ and concordant U-Pb ages on minerals from the same pegmatite, it has been possible to demonstrate first that the K-A and Rb-Sr ages of micas are both consistent over a range of time from 375 to 2700 million years. This and the facts that the ratios, A⁴⁰/K⁴⁰, of several micas from the same pegmatite are in good agreement and a similar agreement exists between ratios, Sr⁸⁷/Rb⁸⁷, on both micas and feldspars, indicate that half-lives of K⁴⁰ and Rb⁸⁷ may be calculated from this geological data with some confidence.

Using the half-lives so obtained and measurements on pegmatites for which no U-Pb ages are available, minerals of ages 2700 m.y. have been found in South Africa, North America, and Western Australia. These are the most ancient reliable terrestrial ages and are much younger than the 4500 m.y. found for the ages of meteorites by Wasserburg and Hayden,¹ Schumacher,² and Patterson, Tilton, and Inghram.³

HANS E. SUESS, *Scripps Institution of Oceanography, La Jolla, California:*
Radiocarbon dating and climatic oscillations during glacial periods. Radiocarbon dates of continental events show that the maximum extent of the ice sheet in North America was reached about 18,000 years ago, and that the oscillating retreat of the ice following this glacial maximum occurred in periods of about 3500 years. Radiocarbon measurements on calcium carbonate from deep-sea cores, investigated by C. Emiliani for paleotemperature variations based on O¹⁸ determinations, indicate a period of approximately 40,000 years for the temperature oscillations of the surface water in the Caribbean Sea. It appears that the last glaciation (Zeuner) embraces at least two of the long periods upon which are superimposed various types of oscillations of shorter periods. The long period coincides with the period in the obliquity of the earth's axis and is predicted by the astronomical theory of climatic variation of Milankovitch. For a final explanation of the glacial oscillations, much more work will be necessary.

J. KAPLAN, *University of California, Los Angeles, California: The International Geophysical Year.** Joseph Kaplan described the International Geophysical Year program. He stated that the idea for an institute of theoretical geophysics arose naturally in early discussions of the IGY venture. The new and rich observational material of the IGY would afford opportunities for theoretical study in many countries for a long time.

L. V. BERKNER, *Associated Universities, Inc., New York, N. Y.: Report on whistlers.* A "whistler" is an electromagnetic phenomenon observed at audio-frequencies (very long wavelengths) by a sensitive amplifier connected to an appropriate antenna. Whistlers were first reported by Potter more than 20 years

¹G. J. Wasserburg and R. J. Hayden, Phys. Rev., **97**, 86 (1955).

²E. Schumacher, Proceedings of Penn State Conference on Nuclear Processes in Geological Settings II, National Research Council publication (in press).

³C. C. Patterson, G. R. Tilton, and M. G. Inghram, Science, **121**, 69 (1955).

*Abstract not supplied by author, but furnished from notes taken during the conference.

ago. The whistler is a descending note, lasting a few tenths of a second. Whistlers tend to appear in multiples, each separated about 2.3 seconds. Preceding the multiple train by about 2.3 seconds, a single pulse like that produced by a lightning-stroke is sometimes observed. This is thought to initiate the train.

The rate of fall of the tone, or "dispersion" of the whistle, diminishes with successive multiples. Whistlers preceded by a pulse appear to have dispersions associated with successive multiples in the ratio of 2, 4, 6, 8, . . . , while those not preceded by the pulse have dispersions in the ratio of 1, 3, 5, 7,

Whistlers tend to occur in "whistler storms" when they can be observed at intervals of minutes. Such storms may be separated by days or weeks when few whistlers are heard. There seems little or no correlation between whistlers observed a few thousand miles apart in the same hemisphere.

The striking aspect of whistlers is the propagation time between multiples, which is very long compared to the transit of waves around the earth, and the low attenuation of successive multiples. Utilizing a simplified form of theory by Eckersley, Storey has proposed that very long waves can travel into space within a tube of force of the earth's magnetic field, provided that the space around the earth contains a few hundred electrons per cc. Such a tube is approximately a circle intersecting the earth at the point of observation, and at a conjugate point in the opposite hemisphere. Since such a tube, intersecting the earth's surface at middle latitude, will pass through space at a distance of several earth-radii above the equator, the path between hemispheres may be long enough to account for the propagation time under suitable conditions for propagation. Thus, Storey has supposed that the observed multiples are reflected successively from the surface at the conjugate and at the observing locations in opposite hemispheres. Since the theory predicts that the longer waves will be propagated more slowly, the increasing ratio of dispersion of successive multiples can be explained.

To test Storey's proposal, Morgan and Allcock have observed simultaneously from conjugate points at Kodiak (Alaska) and in New Zealand. Timing of the experiment was accurately established at both ends from common transmissions of WWVH. They report observation of one coincident whistler in which the multiples of dispersion ratio 2, 4, 6, 8 at one end are accurately interspersed with multiples of dispersion ratio 1, 3, 5, 7 at the other. This is strong evidence favoring Storey's proposals, though a single observation cannot exclude accidental coincidence.

Recently, Helliwell has extended observations to supersonic frequencies, and finds "nose" whistlers in which the dispersion increases from intermediate pitch toward both high and low frequencies. Reexamining Eckersley's theory, Helliwell believes that in its more complete original form the nose whistler may be explained.

In view of its striking characteristics, the whistler is obviously an important phenomenon. If we accept Storey's proposal, the Eckersley theory applied to whistlers may provide a powerful tool for the examination of the space surrounding the earth. Since we have been late in recognizing the importance of the phenomenon, many characteristics of whistlers remain to be explored. These include further observation at the conjugate points, the determination of area over which

a whistler may be heard, the scatter of time intervals separating multiples at a given location, the change of these time intervals with latitude, the dependence of whistler storms on geography, their relationship to meteorological or to magnetic storms (if any), and so on. Much of this work is planned for the International Geophysical Year. A more thorough study of the theoretical aspects of the problem would also be most desirable.

The power of whistler observations suggests that this tool should be brought to the realm of experiment by initiating whistlers artificially in high-powered pulse experiments.

Report of various Committees and Sub-Committees on institute planning, on site, and on finance were presented and discussed

6:30 P.M.—Dinner at Ambassador Hotel

Roger R. Revelle, Chairman

After-dinner speakers: Harold C. Urey and Gerald P. Kuiper

HAROLD C. UREY, *Department of Chemistry and Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*: **Boundary conditions for the origin of the earth and planets.** For many years, astronomers have recognized certain conditions which must be met by any correct theory for the origin of the solar system. The angular momentum is almost entirely in the planets and not the sun. The planetary orbits lie nearly in a plane; the planets move in the same direction around the sun; mostly they rotate on their axes in the same sense with moderate angles of inclination of their axes—Uranus is a marked exception; their satellite systems are similar to the solar system in important ways, and the distances of the planets from the sun follow a regular pattern, the so-called Titius-Bode law. These conditions form the basis of the astronomical discussion of the past which have been most unsatisfactory. Recently von Weizsäcker has made new suggestions, and Kuiper particularly has extended and improved these suggestions markedly.

A number of other boundary conditions have been discovered and discussed in recent years. (1) Aston, many years ago, pointed out that the inert gases had been lost from the earth almost completely. Page (1949) pointed out that this could have occurred only when the solid mass of the planet was distributed over a large volume. The details of such loss have been discussed by several persons, and Suess (1949) in particular. Suess pointed out that the relative proportions of the inert gases of the atmosphere indicate some process of fractionation by loss from a gravitational field.

(2) The terrestrial planets vary in density estimated at zero pressure and hence vary in composition. These densities decrease in the order Mercury, Earth and Venus, Mars, and Moon. Such variations have been discussed for years, but Rabe's new estimate (1950) for the mass of Mercury made this certain. This was

ascribed by Urey (1951) to a variation in the proportions of silicate and iron phases in these objects, and attempts were made to devise fractionation processes to account for this variation. The meteorites indicate that a similar variation in composition exists in at least two groups of meteorites (Urey and Craig, 1953).

(3) The iron of the earth and meteorites occurs partly as the element and partly as the sulfide, oxides, and silicates. Thus, these materials have been subjected to reducing and oxidizing processes which have left the iron in varying valency states (Urey, 1951).

(4) Elements less volatile than mercury have not been removed from the meteorites markedly in accordance with their volatile properties. Thus, arsenic, zinc, and cadmium are present in the meteorites in what are expected to be primordial abundances as compared to their less volatile neighbors in the periodic system. This indicates no escape of the permanent gases in large amounts while these materials were at high temperatures. Limited amounts of water, nitrogen, and carbon have been retained by the meteorites, the earth, and other planets, and this circumstance leads to the same conclusion. The preservation of these elements requires that the solid materials of the planets accumulated at low temperatures, and that all heating processes took place under essentially closed conditions (Urey, 1951, 1954).

(5) There is considerable evidence indicating that some of the planetary bodies were accumulated at low temperatures. (a) The moon has an irregular, non-equilibrium shape on the basis of its dynamical motions. There appears to be no adequate source of energy to accumulate a body of the moon's mass at high temperatures. If it were melted at any time during geologic time, its interior would now be melted and could hardly have sufficient strength to support an irregular shape. If the moon were melted at any time, higher values of the thermal diffusibility are required than are usually assumed for silicates in order to cool it during geologic time. These statements are based on revised calculations such as those made some years ago (Urey, 1951). Gilbert (1893) came to this conclusion, but radioactive heating has required a rather troublesome reconsideration of the problem. (b) Mars has a value for the Clairaut constant ($GM\epsilon/a^3\Omega^2$) which indicates that this planet has from 20 to 30 per cent of iron phase, and yet has a uniform chemical composition throughout (Urey, 1950, 1951). All quantities in this expression—gravitational constant G , mass M , oblateness ϵ , angular velocity Ω , and radius a —are well-established, with the exception of the radius, which enters as the cube. Using the lower reported values of the radius, namely, Trumpler's (1927) value of $0.520 a_{\oplus}$ or Kuiper's (1952) value of $0.523 a_{\oplus}$, and density variations such as those indicated by Bullen's studies of the earth, one comes to the conclusion stated above. Further work on the value of the radius of Mars is indicated and is being undertaken by several members of the Mars committee. (c) Two of the moons of Jupiter have such low densities that they must contain low density material. This must be water or carbonaceous compounds, both of which are volatile at high temperatures (Urey, 1951). (d) The question of the earth's early state is most difficult to estimate. The gravitational energy for the accumulation of the earth was sufficient to melt or even volatilize its substance. If the earth accumulated rapidly, it would be melted, and if it accumulated slowly, that is,

during some 10^7 years, it could have remained in the solid state, except for local and temporary high temperatures. No evidence for increased concentrations of elements which are more volatile at high temperatures, for example, Hg, Cd, Zn, and As, has been found, but it seems that elements have been concentrated at the earth by melting processes and by solubility in water at not more than moderate temperatures (Urey 1953). Current ideas that water and other low temperature volatiles have escaped from the earth's interior are better in accord with a low temperature than a high temperature origin of the earth. About five years ago, the writer suggested certain lines of evidence indicating that iron now exists in the earth's mantle. These have not stood the test of time and scientific discussion well, and no satisfactory evidence of this kind exists.

(6) Recent determinations of the age of the chondritic meteorites have given very definite information in regard to time schedules for the origin of these bodies, and by inference of the earth and solar system. The lead ages were secured by Patterson and coworkers (1953, 1955) in the laboratories of Brown and Inghram. The argon-potassium ages were secured by Gerling and his coworkers (1951) in Russia, by Wasserburg and Hayden (1955) at Chicago, and by Thompson and Mayne (1955) in England. The rubidium-strontium age has been secured by Schumacher (1956) at Chicago. These all agree on an age of 4.3 to 4.6×10^9 years. The $K^{40}-A^{40}$ ages are particularly instructive because this is the time since these objects last lost their A^{40} , and thus since they were heated appreciably. Lower ages reported are probably due to some slight heating since they were formed, but this is not necessarily the correct explanation. These chondrites are conglomerates of rounded chondrules, often of nearly pure minerals, broken crystals, and bits of iron-nickel alloys. Both kamacite and taenite have been observed by Beck, Stevenson, and LaPaz (1951) in LaLande and by Urey (1956) in Beardsley. Thompson and Mayne report an age for the Brenham palasite of about 3.5×10^9 years and, using Edward's (1956) potassium determination, this becomes again about 4.3 to 4.6×10^9 years. Thus, the preparation of the minerals of these objects and these iron-nickel alloys all occurred before 4.3 to 4.6×10^9 years ago, at least in some cases. These objects require that a heating process occurred which melted silicates and iron in the presence of a reducing agent. Then crystallization occurred and a subsequent melting occurred to produce the chondrules. The kamacite and taenite were formed at this time. Then the chondritic meteoritic material accumulated, and this material has not been melted or even heated moderately since then.

(7) These events require some heating process before 4.5×10^9 years. Urey (1951) left the question of the source of this heat unsettled, but had in mind some high-temperature primitive sun (Urey, 1954). However, no astrophysicist seems willing to grant that a new star would become a high-temperature source at this time. Kuiper (1953, 1954) has suggested heating by radioactive elements, although this seems to apply to time after 4.5×10^9 years ago, and does not solve the problem of the minerals of the meteorites. Urey (1955) suggested short-lived radioactive substances, Al^{27} in particular. This requires that the elements were synthesized only a very short time before the origin of the solar system, which is a disturbing assumption on several grounds. Other suggestions have been made in which gravitational energy is the primary source of energy (Urey, 1954). The

Eucken model (1944) uses the Emden gas sphere ideas to produce the earth and its core, but this model does not permit the selective loss of the rare gases, nor does it conform to other chemical requirements.

Another source of energy not previously suggested may have been available. Whipple has suggested an icy core model for comets and has pointed out that the "ices" may have included organic compounds and free radicals. Rice and Freamo (1951) have found that NH may be condensed at low temperatures without reacting to stable molecules, and that it is not destroyed by atomic hydrogen. Donn and Urey (1956) suggest that the flares of comets may result from violent reactions of such free radicals. CH and OH, if reacted to give CO₂ and H₂O, would supply about 4,000 cals per gram. If 10 to 20 per cent by weight of such material accumulated with the silicates at low temperatures, a very rapid heating to the melting points of silicates and iron could have occurred. This source of heat should have been present to some extent, and it may be sufficiently flexible to enable us to account even for the kamacite and taenite (Uhlig, 1955) and the diamonds (Ksanda and Henderson, 1939) of iron meteorites.

No theory for the origin of the solar system meets all these boundary conditions. However, a much more definite knowledge of these conditions is of value in devising such theories. A notable attempt has been made by Kuiper (1951), although his theory antedated most of the evidence above and in many ways it does not meet the conditions. Urey (1954) attempted some modifications, but none of these seem satisfactory. The Soviet scientists of the school of O. J. Schmidt (1955) have introduced large objects collected at low temperatures into their theory of the solar system from the beginning, but it is not yet possible to see how the conditions set forth above will be met in detail. Perhaps we are approaching the time for a new approach to the entire problem.

References

- Beck, C. W., R. G. Stevenson, and L. LaPaz (1951); *Cont. Meteoritical Soc.*, **5**, 11; *Pop. Astr.*, **59**, 93.
- Donn, B., and H. C. Urey (1956); *Astrophys. J.* (in press).
- Edwards, G. (1956); *Geochim. et Cosmochim. Acta* (in press).
- Eucken, A. (1944); *Nach. Akad. Wiss., Göttingen, Math.-phys. Kl.*, Heft 1, S. 8, 9.
- Gerling, E. K., and T. G. Pavlova (1951); *Doklady Akad. Nauk, U.S.S.R.*, **77**, 85.
- Gilbert, G. K. (1893); *Bull. Phil. Soc. Wash.*, **12**, 241.
- Kuiper, G. P. (1951); *Astrophysics*, J. A. Hynek, Ed., New York, McGraw-Hill Book Co., Inc.; chap. 8.
- (1952); *Atmospheres of the earth and planets*, Chicago, University of Chicago Press.
- (1953); A.A.A.S. meeting, Boston, December.
- (1954); *Proc. Nat. Acad. Sci.*, **40**, 1096.
- Ksanda, C. J., and E. P. Henderson (1939); *Amer. Min.*, **24**, 677.
- Page, T. (1949); *Smithsonian Inst. Rep., Pub. 3998*, 161.
- Patterson, C. (1955); *Geochim. et Cosmochim. Acta*, **7**, 151.
- , H. S. Brown, G. Tilton, and M. Inghram (1953); *Phys. Rev.*, **92**, 1234.
- , G. Tilton, and M. Inghram (1955); *Science*, **121**, 69.
- Rabe, E. (1950); *Astroph. J.*, **55**, 112.
- Rice, F. O., and M. Freamo (1951); *J. Amer. Chem. Soc.*, **73**, 5529.
- Schmidt, O. J. (1955); *Les particules solides dans les astres*, Mem. Soc. R. Sci. Liège, Quad. Ser., **15**, Fasc. Unique; see the references given in this paper.

- Schumacher, E. (1956); *Zs. Naturf.* (in press).
- Suess, H. E. (1949); *J. Geol.*, **7**, 600.
- Thompson, S. J., and K. I. Mayne (1955); *Geochim. et Cosmochim. Acta*, **7**, 173.
- Trumpler, R. J. (1927); *Lick Obs. Bull.*, **13**, 19.
- Uhlig, H. H. (1955); *Geochim. et Cosmochim. Acta*, **7**, 34.
- Urey, H. C. (1950); *Phys. Rev.*, **80**, 295.
- (1951); *Geochim. et Cosmochim. Acta*, **1**, 209.
- (1953); *Proc. R. Soc., A*, **219**, 281.
- (1954); *Astroph. J., Sup.*, **1**, 147.
- (1955); *Proc. Nat. Acad. Sci.*, **41**, 127.
- (1956); Recent observations.
- , and H. Craig (1953); *Geochim. et Cosmochim. Acta*, **4**, 36.
- Wasserburg, G. J., and R. J. Hayden (1955); *Phys. Rev.*, **97**, 86.

GERARD P. KUIPER, Yerkes Observatory, Williams Bay, Wisconsin: **The origin of earth and planets.** 1. *Introduction*—The problem of the origin of the earth cannot be treated apart from the more general problem of the origin of the planets and the solar system—anymore than the solar origin from the origin of the stars and the stellar system; or the origin of North America from the origin of continents in general. The wider context, resulting from consideration of the entire problem of planet formation, leads at once to important additional clues, dynamical and astrophysical, which enable one to find at least certain aspects of the solution. These aspects include the processes of planetary segregation, the determination of the approximate initial masses—which are very much larger than the present planetary masses—and at least qualitative explanations of the present gross compositions of the planets, their sense and rough amount of rotation, their equatorial obliquities, and their satellite systems. Nevertheless, there is still a considerable gap between the astronomical picture of planet formation and the detailed geophysical picture of the present earth or the corresponding astronomical picture of the other planets. Moreover, the earth-moon system, far from being the best understood, is in many respects the least understood. This is due largely to the fact that the moon is not a true satellite but forms with the earth a double planet, the only case of its kind in the solar system. This unusual mass distribution led to an unusual distribution of angular momentum which, coupled with an exchange of angular momentum by tidal friction, has caused the evolution of this system during geologic time to be exceptionally active and entirely unlike any other system accessible to study. While the study of the planetary system and its origin has thus led to a general framework in which the *origin* of the earth-moon system can be understood, some of the most interesting geophysical problems stem directly from this peculiar duplicity and are characteristic of the earth alone.

In this brief paper, the present status of some of the principal problems of origin can at best be merely indicated; a somewhat fuller report (about 50 pages in print) on the same subject was recently prepared and is being published elsewhere. For brevity, no references will be given here; they may be found in the longer report.

The earth and the meteorites are nearly five billion years old, while a similar age is found for the sun. This can hardly be accidental and suggests that the formation of the sun and of the planets were related and, in fact, part of the general

process of star formation. This surmise is confirmed by further study. The essential point is that a contracting protostar, starting with a probable diameter of about half a parsec (that is, somewhat less than interstellar distances), must contract linearly by a factor of some 10^7 before becoming a stable star on the main sequence, like the sun. Because of conservation of angular momentum, the slightest anisotropy in the initial motions, whose magnitudes may be estimated from observed properties of interstellar material, will cause the total angular momentum to be well in excess of what a stable star in rapid rotation can possess. As a result, the mass will in general break up into components whose mutual orbital motion can take on this substantial total angular momentum. Binary and multiple stars thus ought to be rule rather than exception—and this is actually the case. Their separations are a measure of the initial angular momentum present; the distribution of separations, observed among a statistically homogeneous set of nearby stars, is shown in Figure 1. The arrow marks the position of the major planets with respect

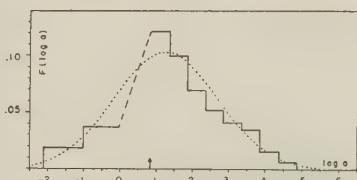


FIG. 1—Frequency curve of semi-major axes, a , of binary stars for a volume of space surrounding the sun, after correction for incompleteness. *Abscissae:* $\log a$ in astronomical units; *ordinates:* frequency per unit interval of $\log a$ of binaries with magnitude differences between components less than 4 magnitudes (corresponding to mass ratios smaller than about 3 to 1). The distribution of mass ratio appears to be nearly independent of a and the total number of binaries, with all mass ratios, is about twice that under the curve.

to the sun; it is seen that the dimension of the planetary system is typical of that of binaries. Planetary systems can be shown to result in those cases where the secondary mass is less than about 0.1 of the primary mass and where, moreover, the secondary mass is spread out radially enough to prevent the formation of a single stellar companion and to cause instead a string of planets. From the empirical result that the masses in the binary stars divided very nearly at random between the components, one can make an estimate of the frequency of planetary systems in the galaxy. One finds a figure between 1 and 10 per cent of the stars, or some 10^{10} planetary systems in the galaxy alone.

The further discussion falls under two main headings: (a) Origin of planets, as separate bodies, and (b) subsequent planetary evolution. Since in principle problem (a) can be formulated only after (b) has been solved, by going back in time from the present, we must review (b) first.

2. *Planetary evolution*—We can here only enumerate the chief problems and their indicated solutions or difficulties. The *solar luminosity*, which affects planetary evaporation and composition, has slowly increased over the past five billion years, by some 20 per cent, following an initial period of some 80 million years during which the sun passed through its contraction stage. Almost certainly the sun was

never brighter than at present. Planetary evaporation, now insignificant, must therefore be presumed to have been unimportant ever since the time of planet formation. This implicitly assumes that the planetary distances from the sun have not altered appreciably. This is found to be the case. Hence, a theory of origin must account for the present values of the *planetary masses* and gross *compositions*. Internal rearrangements, however, are known to have occurred on the earth, at least near the surface (continent formation, etc.). Also on Jupiter and Saturn there is evidence for change; the equatorial accelerations indicate that material collapsed onto the planet possessing more angular momentum per unit mass than the planet itself, and therefore presumably derived from the interior part of the protoplanet envelope.

Solar mass changes (by ejection or accretion) are found to be unimportant, so that the present *solar mass* may be used with some confidence. The *distance* changes of the terrestrial planets from the sun have probably been quite small, as based on analyses of the secular variations of the orbital elements; no such statement can be made for the Jovian planets, where 10^8 years of orbital stability is the most that the analysis can guarantee. Evidence from the theory of origin, however, based on a comparison of protoplanet masses computed dynamically and from present planetary compositions, indicates that Saturn and Uranus may have changed their orbital radii by as much as 5 to 10 per cent since these planets were formed; while Jupiter and Neptune appear to have changed much less. The *orbital eccentricities* and *inclinations* undergo "secular" variations, which are in reality sums of periodic functions, with periods of 10^5 to 10^6 years. Figure 2 shows the maximum

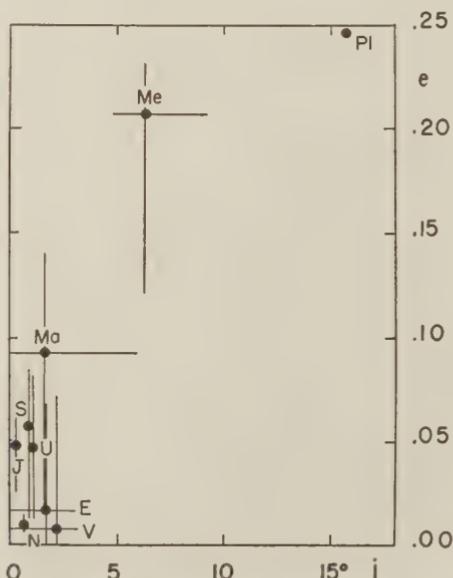


FIG. 2—Planetary orbital eccentricities *vs* orbital inclinations with respect to invariable plane. Dots indicate present values; lines, total range of secular variations according to Stockwell.

amplitudes of these variations for periods less than 10^8 years, intervals for which the analysis should be valid. There is uncertainty, however, as to what may have happened for still longer periods. Yet, it is very probable that the initial eccentricities and inclinations were not larger, but may have been smaller, than the modern values. The *obliquities* of the planetary equators on their orbits and the *periods of rotation* can have changed only very little, because of (a) the negligible mass losses and (b) the small angular momenta carried by the satellites compared to those of the planets themselves. The one exception is the earth-moon system, where the moon carries at present 4.8 times as much angular momentum as the rotating earth, and where, moreover, an exchange mechanism is active owing to tidal friction.

In summary, it is found that for the sun, the planets, and the 31 known satellites, the modern values of the physical and dynamical constants may be used back to the time just following the period of planet formation, except for the earth-moon system and, to a lesser extent, some pairs of planets and satellites where near-commensurabilities in the mean motions have probably caused minor systematic shifts in the orbital elements. After this brief review of the possible evolutionary changes during geologic time, the problems of origin may be taken up with somewhat greater assurance.

3. *Planetary origin*—The problem before us is to account for the existence of planets, their orbits, masses, and gross compositions; their satellite systems, axial rotation, and obliquities; and, incidentally, the formation of asteroids and comets. Not included will be the subsequent, but still pre-geological, internal development of the planets, their detailed compositions, surface temperatures, heat balance, etc., subjects partly geochemical in nature.

The modern picture, of the planets forming from a nebula surrounding the sun (solar nebula), resembles the Kant-Laplacian hypothesis. Why then was that hypothesis abandoned by most students at the turn of the century? It had two major defects: (a) The nebula, supposed to possess the same total mass and total angular momentum as the present planets (called *Babinet's criterion*), could not form planets by gravitational effects—it was too tenuous for self-gravity to be important; (b) the sun would be expected to have formed with the maximum amount of rotational momentum compatible with stability; instead it has 200 times less.

Difficulty (a) was being overcome a decade or two ago when astrophysicists found that the sun, the stars, and even interstellar material were all of similar, "cosmic," composition; and that the earth, composed of heavy non-volatiles was, so to say, a cinder compared to the gaseous universe. The planetary masses, therefore, must have been derived from much larger masses of cosmic composition, either directly by condensation, or gradually by accretion. In any case, since the differentiation could not have occurred previously in the interstellar gas, the solar nebula must initially have been much more massive than the combined masses of the present planets, by a factor of 30 to 40 times. With this increased mass, and at a sufficiently low temperature, the density of the nebula would indeed be high enough for self-gravity to become effective.

The second difficulty could be removed after the effects of magnetic fields on

ionized matter had been studied and it became clear that a rotating star with an extended ionized envelope could lose angular momentum to that envelope.

Several schemes of planetary origin proposed in recent years are based on the assumption that Babinet's criterion applies. It can be shown that planet formation under these restrictions is not possible. Only a swarm of cometary and meteoric bodies would result.

One may now state the problem as follows: If it be assumed that the planets were formed in their present positions from protoplanets, which at the time of the break-up of the solar nebula essentially touched radially and thus divided the solar nebula between themselves, what are the numerical values of the masses required in order that these protoplanets be stable in the tidal field of the sun? It was found that "on the average, somewhat less than one per cent of the mass of the protoplanets condensed into the planets themselves. This fraction is quite reasonable in view of the known planetary composition." Actually, one can improve the picture by stating that the larger planets retained a larger fraction of their initial mass and have at present still an excess of free hydrogen; while the smaller, or terrestrial, planets retained only 0.001 to 0.002 of the initial protoplanet mass, in accord with their special composition.

It thus appears that the protoplanet masses were determined by stability conditions in the tidal field of the sun. But this is no complete explanation. It merely states that, given the planetary distances, the initial masses can be computed and that these masses are in accord with other evidence. But what determined the planetary distances? These are found to depend on the local *density* of the solar nebula, expressed in a unit which under certain conditions varies as the universe cube power of the distance from the sun. If the density, expressed in this unit, is large, a binary-star companion will form; as it decreases, the protoplanet mass will decrease sharply, until below a certain limit (which still weakly depends on the temperature) no gravitational collection process can occur at all. Below this limit, condensation will still take place, but it will resemble the kind of condensation one observes in a rain cloud. Only a swarm of particles will form.

Closer examination of the segregation process shows that there are two stages: (a) Amplification of initial random density fluctuations by gravitational instability, which will occur if a certain critical limit depending on density and temperature is surpassed; this process will in time lead to the formation of clouds which are stable in the tidal field of the sun; (b) growth of the tidally stable clouds by gravitational acquisition of neighboring matter. Because the mass of tidally stable clouds must increase as the cube of the diameter and because the mass of a torus in the solar nebula will increase linearly with its width, the upper limit to which the protoplanet can grow is sharply defined by the local density in the solar nebula. The criteria for the onset of gravitational instability must and have been developed for nebulae of *finite dimension*, which are in *rotation*, and which may be *turbulent*.

In this manner, a unified theory for the origin of planets and binaries is developed, which is schematically illustrated in Figure 3. From the present planetary distances, the initial mass distribution in the solar nebula may be derived. This is done in Figure 4. The nebula contains three regions where the density fell below

the critical value below which no protoplanets can form; inside the Mercury orbit, between Mars and Jupiter, and outside Neptune. In the last two, the temperature was low enough for condensation products to form: the *asteroids* and the *comets*, respectively. Since the distance of the comet zone was about 10 times the distance of the asteroid zone, the nebular density will have been some 10^3 times smaller. Therefore, the comets are some 10^3 times smaller than the asteroids, roughly 1 km vs 10^2 to 10^3 km, accretion being roughly proportional to the density.

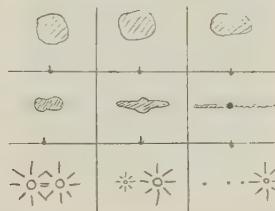


FIG. 3—Development from prestellar cloud of, *left*: a binary star with equal components; *center*: a binary with unequal components; *right*: a planetary system. The scale changes by a large factor between consecutive rows (schematic).

The fact that planets did not form everywhere in the solar nebula shows that the limit at which gravitational instability could set in was passed at certain known points. Because the protoplanet masses can be estimated from present planetary compositions, and since gravitational instability is temperature- as well as density-dependent, a rough estimate may be made of the *temperature* of the solar nebula at the time of break-up. This “temperature” is not necessarily the thermal temperature of the molecules, but is the equivalent kinetic temperature that includes turbulence effects. It is found to be about 40°K near the present

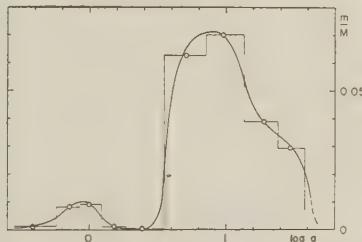


FIG. 4—Computed radial mass distribution within solar nebula before the latter broke up into protoplanets. *Abscissae*: $\log a$ in astronomical units; *ordinates*: mass per unit interval in $\log a$, expressed in fractions of the solar mass.

earth and somewhat lower farther out. These values are no higher than would be expected from the cooling of the solar nebula to space over an interval of 10^6 to 10^7 years, before the sun got bright. Therefore, the *turbulence motions* were no larger than the thermal motions of hydrogen, some 0.5 km/sec. It can further be shown that turbulence must have decayed during the life of the solar nebula, a

result of conservation of angular momentum but loss of energy by turbulence dissipation. The decay cannot have been complete, however, or the planets would later have had zero orbital inclinations and zero obliquities. The appearance of the solar nebula before break-up and the resulting protoplanets are shown schematically in Figure 5.



FIG. 5—*Above*: Schematic views of solar nebula before break-up into protoplanets; *below*: after the break-up. The break-up occurred before the sun was luminous, at temperatures around 30 to 50°K.

The birth of the planets in the solar nebula explains their *nearly circular orbits of low inclination*. It has further been shown that sedimentation in the solar nebula toward the sun was extremely slight and had no effect on the composition of the protoplanets. Genuine protoplanets, therefore, started with the cosmic composition. Mars and Mercury were initially not genuine protoplanets, because gravitational instability could not set in until appreciable sedimentation toward the plane of symmetry of the nebula had taken place. Pluto is found to be no planet at all, but to have originated as a satellite of Neptune.

4. *The protoplanets, properties, and evolution*—For the protoplanets whose masses may be determined independently, it is possible to find the actual fraction which they covered of the width of the ring around the sun. It is found to be about 0.5. This fraction should be determinable theoretically also, but this difficult problem has not yet been solved. The *rotation* of the protoplanets was synchronized early in their existence with the orbital rotation, owing to solar tidal friction. Later, as the masses shrank, the rotation became *direct*, at all distances from the sun. The same follows for the subsequent satellite motions.

The protoplanets were initially disk-shaped; it can be shown that they were intermediate in mass concentration between the extremes of homogeneous density and high central concentration.

A dramatic change in the solar system occurred when the sun "turned on." This event, while of course not instantaneous, was nevertheless rather sudden, astronomically speaking; and it almost destroyed the protoplanets. First, the remnants of the solar nebula became ionized and were swept away by corpuscular radiation, as still happens at present to comet tails of Type I. Thereupon, the protoplanets themselves were affected; they developed exospheres and could evaporate to interplanetary space in which the mean free-path was kept low through the constant sweeping by solar particles. Figure 6 shows schematically the inner protoplanets just after the sun had attained full brightness.

From energy considerations, one finds the time scale of the evaporation was between 10^8 and 10^9 years for the different protoplanets. Practically nothing but

solid cores were left to the terrestrial planets; but for the Jovian planets, particularly Jupiter and Saturn, large quantities of H₂ and He could be retained. The history of the evaporating protoplanets is complex and cannot be traced in any detail here. It involves the formation of satellites, which apparently occurred during two periods, separated by an interval in which no satellites formed. This interval probably coincides with the rapid brightening of the sun, which probably caused at first the protoplanets to be highly turbulent. The regular satellite systems were formed during the last phases of the protoplanet stage, when the total masses were reduced to nearly the present planetary masses.



FIG. 6—Inner three protoplanets after the sun completed its contraction, had attained full brightness, and had begun to dissipate the gaseous envelopes of the protoplanets. Presumably the planets at that stage looked like giant comets.

The protoplanet evaporation was responsible for large increases in the *planetary obliquities*, owing to the fact that the angular momentum lost by evaporation was related to the position of the sun (and, therefore, the planetary orbit) and not exclusively to the position of the planetary pole of rotation. It can be shown that as a result the pole became increasingly inclined to the orbit, as mass was lost by evaporation. Solar tidal friction has a similar effect, but is quantitatively less important. Further, effects of the large mass losses include the dropping of the more distant satellites into interplanetary space, from which they could later be recaptured, as *irregular* satellites. Or else, they could be pressed into orbits of the *Trojan* type; or into orbits of the Hidalgo and Pluto type.

In conclusion, attention is called to the general confirmation which the theory has derived from recent results—the period of rotation of Pluto and the mass decrease of proto-Jupiter found by Rabe from asteroids. For the earth, confirmation is derived from the abundances of the inert gases.

Friday, February 3, 9:00 A.M.—12:30 P.M.

Carl Eckart, Chairman

C. L. PEKERIS, *Department of Applied Mathematics, The Weizmann Institute, Rehovot, Israel: Research on the oscillations of the earth and theoretical seismology.*

A. *Oscillations of the earth**

The problem of the oscillations of the earth, both of the free and of the forced type, needs to be reexamined in view of the following recent developments:

(1) Benioff (Trans. Amer. Geophys. Union, 35, 985, 1954) has observed an

*Research supported by ONR under Contract Nonr-1823 (00).

oscillation of a period of 57 minutes on the records of the Kamchatka earthquake of 1952. This observed period is close to a theoretical free period of one hour which Love computed in 1912 for a uniform earth, having the rigidity of steel. It is of interest, therefore, to determine (a) whether the real earth, as we know it today from earthquake data, has this free period of oscillation; and (b) why, and whether, only the 1952 Kamchatka earthquake excited this free oscillation.

Preliminary results which Mr. H. Jarosch and I have obtained so far on this problem indicate that Love's value of a period of one hour for spheroidal vibrations is likely to be an overestimate, since the average rigidity of the earth is about 1.8 times greater than that of steel, even allowing for the liquidity of the core.

Indeed, the period of spheroidal vibrations of a uniform gravitating sphere having the mean rigidity, bulk modulus, and density equal to that of the earth is 44 minutes and 17 seconds. The period for the real earth is now being computed.

(2) The continuous records of high precision of the bodily tide of the earth, which Slichter and Lacoste are obtaining, call for a reexamination, in greater detail than has been done hitherto, of the theory of forced oscillations of the earth. This problem can, unfortunately, not be disentangled from the problem of the oceanic tides, as is evidenced by the marked effect which the proximity to the ocean has on the observed bodily tide. Hence, a successful solution of the problem of the bodily tide spells equal success with the problem of determining the tides in the actual oceanic basins with their irregular boundaries, and *vice versa*.

It is hoped that a way will be found of formulating the problem of oceanic tides in the language of electronic computers.

B. Theoretical seismology

When I spoke of the real earth, I had in mind a *model* of the earth as determined or inferred from earthquake data and other geophysical data. Now, current methods of interpretation of records of earthquakes, whether the latter are of natural or artificial origin, are based largely on ray theory, and not on the complete wave theory. We glean from the records mainly the arrival times of the different rays, and make little use of the shape of the record between the arrival times. With the advent of electronic computers, it should be possible to compute the complete motion of the ground caused by an explosion of specified nature.

Taking the simplest problem of this kind, the motion of the surface of a uniform elastic half-space produced by an explosion situated at a depth H below the surface, one is confronted with the mathematical problem of solving for $W(t, r, z)$ the vertical component of the surface motion, say, from the integral-equation

$$p \int_0^\infty e^{-pt} W(t, r, H) dt \\ = \frac{p}{c} \int_0^\infty J_0\left(\frac{p}{c} rx\right) f(x^2, \sqrt{x^2 + a^2}, \sqrt{x^2 + \lambda^2}) \exp\left\{-\frac{p}{c} H \sqrt{x^2 + a^2}\right\} x dx. \dots (1)$$

Here f is a rational function of its arguments, c denotes the wave velocity, and a and λ are constants related to the values of the compressional and shear velocities in the medium.

The solution of integral equation (1) is simplest when $\lambda > a$, corresponding to the case of a dilatational source, when it takes on the form

$$\left. \begin{aligned} W = 0, \quad \theta \equiv \frac{ct}{aR} < 1, \\ W = \left(\frac{2a}{\pi R} \right) \operatorname{Re} \int_0^{\pi/2} (h\theta + i\mu_0 \sin \varphi) f(a \sqrt{(h\theta + i\mu_0 \sin \varphi)^2 - 1}) d\varphi, \quad \theta > 1 \end{aligned} \right\} \dots (2)$$

where

$$\left. \begin{aligned} R = \sqrt{r^2 + H^2}, \quad h = \frac{H}{R}, \\ \mu_0 = \sqrt{(1 - h^2)(\theta^2 - 1)}, \quad x = a \sqrt{(h\theta + i\mu_0 \sin \varphi)^2 - 1} \\ \sqrt{x^2 + a^2} = a(h\theta + i\mu_0 \sin \varphi), \\ \sqrt{x^2 + \lambda^2} = \sqrt{a^2(h\theta + i\mu_0 \sin \varphi)^2 - a^2 + 1}^2 \end{aligned} \right\} \dots \dots \dots (3)$$

The solution (2) is in a form easily put on an electronic computer. Each point on the W -curve requires the computation of a complex integral, but a modern electronic computer prints out the answers almost as fast as one can read in the parameters of the integral.

When the explosion at the source is of the shear type, or of the mixed type, the solution of the integral-equation (1) is more complicated, due to diffraction, but is still of the same nature, and thus readily solvable with the aid of an electronic computer. In Figure 1 are shown the results of such computations carried out

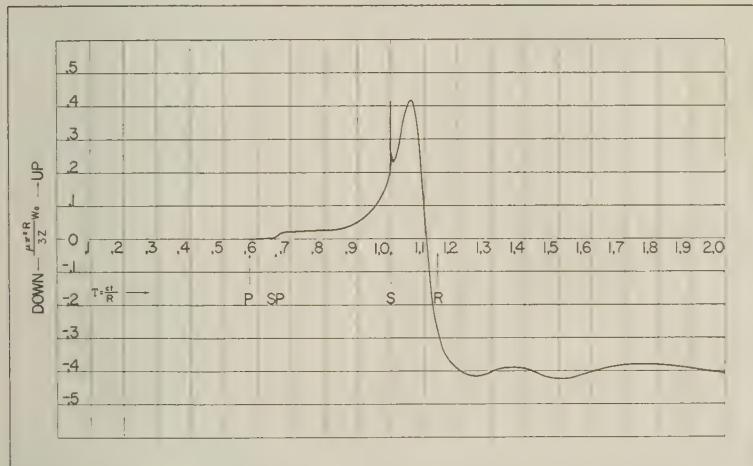


FIG. 1—Vertical component of displacement w_0 of the surface of a uniform elastic half-space produced by the application of a downward force at a depth H below the surface. Distance r from epicenter is equal to $10H$.

recently on the electronic computer of the Weizmann Institute, which is an offspring of the computer at the Institute for Advanced Study in Princeton. The ordinate represents the vertical component of the motion produced by the appli-

cation of a *downward force* varying in time like the Heaviside unit function. You note the following:

- (a) The relatively weak P-wave
- (b) The much more intense beginning of the diffracted SP wave
- (c) The *logarithmic infinity* at the time of the arrival of the S-wave
- (d) The strongly marked Rayleigh wave
- (e) The oscillations following the arrival of the Rayleigh wave

The source corresponding to a downward force is composed of a dilatational and a shear component. The motions due to these separately are shown in Figure 2.

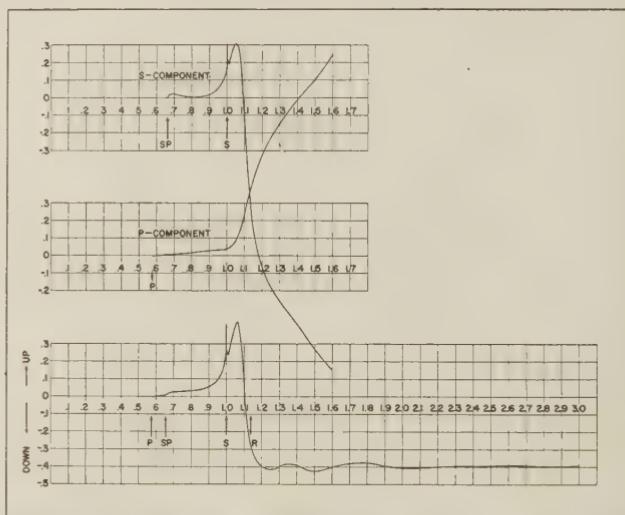


FIG. 2—The contributions to the vertical displacement w_0 from the shear component and the dilatational component of the source.

Finally, I shall add that the above analysis is adequate for tackling the following problems in wave propagation:

- (1) The theory of the refracted wave at a surface of discontinuity in an elastic medium (refraction shooting)
- (2) The wave theory of underwater explosions in the region close to the source where the normal mode theory is inapplicable
- (3) Propagation of an electromagnetic pulse from an antenna near a non-conducting ground

I believe that the possibility is at hand of deepening our techniques of interpretation of seismic records.

R. STONELEY, *Department of Geodesy and Geophysics, Cambridge, England*:
Surface elastic waves. The theory of surface elastic waves in a medium in which the density and elastic constants are functions of the depth below the free surface

shows that the propagation is dispersive. The curve representing phase-velocity as a function of wavelength has much the same form for a wide range of variation in the model chosen, and this precludes the possibility of deriving directly from the group-velocity, as observed in the long-wave phase of seismograms, a unique constitution for the surface layers, whether continental or oceanic, corresponding to an assigned track. However, by assuming a layered structure of the type indicated by near earthquakes and explosion records, comparison may be made with observed velocities and periods of surface waves.

The theory of Love waves in a double surface layer, corresponding to a layer of granite T_1 km thick and a lower layer of basalt T_2 km thick, resting on ultra-basic material of great thickness, gives a relation

$$2T_1 + T_2 = 65 \text{ km}$$

for Eurasia. The corresponding theory for Rayleigh waves gives

$$2T_1 + 1.3T_2 = 73 \text{ km}$$

These relations are admittedly rough, and there is ground for believing that the T_2 layer may be rather local in character; for approximate isostatic equilibrium, the granitic layer should vary considerably in thickness from place to place. Combined with other seismological evidence, there is approximate agreement if we take $T_1 = 25$ km, $T_2 = 10$ km, and this estimate is reasonably consistent with measures of heat flow.

The phase-velocity equation corresponding to a double surface layer under the ocean is in process of coding for solution by the SEAC machine at the National Bureau of Standards.

Some attention has recently been given to the propagation of surface elastic waves in anisotropic media. Waves of Love and Rayleigh types can exist in "transversely isotropic" media, and the theory has found an application to a problem in seismic prospecting. The theory of the propagation of surface waves over a cubic crystal is more intricate, and shows that the two types of surface waves in an isotropic medium are mathematically degenerate cases of a more complicated kind of wave motion.

WALTER ORR ROBERTS, High Altitude Observatory of the University of Colorado, Boulder and Climax, Colorado: **Solar coronal temperature and emission.** Two forms of emission from the sun's corona appear to have particular geophysical significance. The first of these is corpuscular emission, the direct observational evidence for which is the appearance of the "K-corona" or "electron corona," which shows as a white streamered halo about the sun at times of total eclipse. G. Wlérick and James Axtell, of our staff, hope soon to initiate observations of this component of the solar corona on a day-to-day basis. Only the Pic du Midi Observatory, in France, now observes the K-corona outside of eclipse, and even there the observations are limited in frequency and nature. There is good reason to believe that K-corona streamers, when they sweep the earth, produce auroral, geomagnetic, and meterological effects.

Another form of coronal emission occurs in connection with regions of unusually

high temperature. These have been extensively studied by M. Waldmeier, of the Swiss Federal Observatory, and others. D. E. Billings, H. Zirin, and Sanford Schwartz, of the High Altitude Observatory staff, are working on problems of the basic physics of these regions, which are characterized by the emission of strong coronal spectrum lines from atoms in high stages of ionization (Fe X, Fe XIV, Ca XV, etc.) and by coronal spectrum-line profiles that are very broad and that are generally Gaussian in form. Their widths reach values of over 0.9 Å, corresponding to kinetic temperatures over 3×10^6 °K; they are rarely below 2×10^6 °K. We are of the opinion that these wide profiles are usually thermal, and that the regions are therefore hotter than previously supposed. These regions are probably responsible for the origin of highly variable solar emission in the far ultraviolet and the soft X-ray regions, and, in particular, for radiations in the range from 1 Å to 50 Å, discussed by Friedman and Chubb of the Naval Research Laboratory. Such emissions must have geomagnetic and meteorological importance.

We conclude, from several lines of reasoning, that these high temperatures extend to very low levels in the solar atmosphere, and, in fact, to within the solar chromosphere. We speculate, following suggestions of R. N. Thomas, of Harvard Observatory, that the high coronal temperatures are, at least in part, a result of the conversion of kinetic energy of the directed motion of fast-traveling prominence streamers into thermal energy in the static corona surrounding the prominences. On this question, we hope soon to develop arguments and observational data of a more quantitative sort.

B. GUTENBERG, *California Institute of Technology, Pasadena, California:*
Discussion of changes in climate. The basis of the Milankovitch theory should be improved, not only as far as the astronomical constants are concerned, but also by considering effects of the simplification introduced by using only the half year with the largest solar radiation in a given latitude, regardless of its effect on the climatological elements.

2:00—5:00 P.M.

E. H. Vestine, Chairman

Informal discussion of uses of IGY world-wide data in the solution
of geophysical problems; actions and recommendations
of the conference

B. GUTENBERG, *California Institute of Technology, Pasadena, California:*
Uses of International Geophysical Year world-wide data in the solution of geo-physical problems. During the IGY, observers in many countries will become familiar with various types of modern methods of recording, observation, interpretation of results, etc., and many instruments will remain in those countries. For the evaluation of observations, it is more important to reduce and analyze well-selected data by the best possible methods than to study all available data by less time-consuming but less accurate methods. For example, in calculating

gravity anomalies, any known data on local structure of the crust and on its density should be considered. Electronic calculators should be used whenever practicable. An important result (emphasized by the present meeting) is that specialists in all sections of geophysics get a better mutual understanding of their findings and methods; this results in less frequent use of assumptions shown to be impossible by results in other fields of geophysics and in a more unified picture of the properties of the earth and the processes involved in its development.

There was an afternoon session on the uses of IGY world-wide data for the solution of global aspects of geophysical problems, and final business session. It was noted that IGY data would yield much useful material and would provide a basis for student theses, as well as material for other investigators. Sydney Chapman, President of the Special Committee of IGY, discussed especially the opportunities for fruitful study, by way of example, in the case of the aurora, geomagnetism, the ionosphere, and other atmospheric studies. S. E. Forbush continued the discussion mainly on cosmic rays and related phenomena in solar and earth physics. B. Gutenberg discussed the uses of IGY data on problems of the earth's interior, which would benefit greatly by the improved coverage, for example, from added seismic stations in the southern hemisphere. Helmut Landsberg staggered almost everybody by reporting that there were 300 million punched cards covering recent Weather Bureau data, and that these were added to at the rate of 60,000 or so a day. It was observed that storage of such data which had already seen their initial use did not imply any future obligation to use them, but that they could be used as needed when of value in meterological research or for other purposes.

A number of actions were then taken by the conference unanimously. It was agreed that there was a clear need for more theoretical work in geophysics. Each institution with a program in scientific geophysics was urged to intensify its activities in theoretical geophysics. It was agreed that there is now a need for at least one major institute which may devote its primary attention to the theoretical and mathematical aspects of geophysics. The coverage in geophysics should be broad and not restricted to certain branches. The institute should be associated with or an integral part of a university. Financial support from the parent or host institution, private foundations, government sources, business and industry would be sought. After an initial capital outlay, grants and contracts would prove helpful to maintain the activities. It is anticipated that adequate funds for pre- and post-doctoral fellowships and assistantships would be made available.

Several universities indicated they would plan to provide their own theoretical groups, whether or not they were invited to provide a home for a new institute. The following universities had already expressed interest in providing a home for an institute: California Institute of Technology, University of Chicago, Columbia University, Harvard University, Massachusetts Institute of Technology, Ohio State University, Princeton University, Rice Institute, University of California, University of Colorado, and the University of Hawaii.

The conference also recommended that substantial grants be made during the next three to five years to institutions having outstanding records in accomplishment in training advanced students in experimental and theoretical

research in geophysics, with the specific aim of a substantial intensification of their activity in scientific geophysics over a period long enough for them to develop strength in their permanent program of research and training in this field. The conference also recommended that non-project grants for the training and support of students, and laboratory and field operations without restriction as to problem or project, be made to productive institutions. Other recommendations covered release of classified information on high-pressure apparatus, purchase of a ship for the Lamont Geological Laboratory, and a recommendation was directed to the National Science Foundation to appoint an Advisory Panel on Geophysics, with a Sub-Committee on Theoretical Geophysics, to continue the work of the present Steering Committee until such action.

The conference recommended that the site of the theoretical institute be where there is already experimental research and teaching in geophysics.

It was noted that at least one major institute could be formed by collecting several groups of potential key personnel expected for various reasons to be forced to move or expecting to move from their present locations in the course of the next few years. Thus, one or more institutes formed at this time would be likely to least disturb existing facilities. Faculty positions in theory, closely associated with existing experimental research at a site, would no doubt result at some locations. The experts present unanimously indorsed the concept of providing at least one broad spectrum institute, resulting in faculty positions in geophysics covering about 15 areas of geophysical interest, with a very modest effort per area. There were other recommendations urging provision of faculty positions in both theory and experiment, so that very flexible means of implementing the recommendations of the conference were suggested.

The conference completed its heavy load of scientific study and work, in a spirit of friendly and effective cooperation unusual for so large and assorted a gathering.

The following invited participants attended the Conference on Theoretical Geophysics:

- P. H. Abelson, Geophysical Laboratory, Carnegie Institution of Washington
J. N. Adkins, Office of Naval Research
L. T. Aldrich, Department of Terrestrial Magnetism, Carnegie Institution of Washington
J. R. Balsley, Jr., U. S. Geological Survey
W. H. Bennett, Naval Research Laboratory
W. E. Benson, National Science Foundation
L. V. Berkner, Associated Universities, Inc.
H. G. Booker, Cornell University
H. S. Brown, California Institute of Technology
W. H. Bucher, Columbia University
H. R. Byers, University of Chicago
J. W. Chamberlain, Yerkes Observatory
S. Chandrasekhar, Yerkes Observatory

- S. Chapman, University of Alaska
J. G. Charney, Institute for Advanced Study
G. M. Clemence, U. S. Naval Observatory
C. Croneis, Rice Institute
E. G. Droessler, The Pentagon
C. Eckart, Scripps Institution of Oceanography
W. M. Elsasser, University of Utah
M. Ewing, Columbia University
J. W. Firor, Department of Terrestrial Magnetism, Carnegie Institution of Washington
S. E. Forbush, Department of Terrestrial Magnetism, Carnegie Institution of Washington
F. N. Frenkiel, Applied Physics Laboratory, Johns Hopkins University
D. Fultz, University of Chicago
R. M. Gallet, National Bureau of Standards, Colorado
N. C. Gerson, Air Force Cambridge Research Center
R. Gunn, U. S. Weather Bureau
B. Gutenberg, California Institute of Technology
W. A. Heiskanen, Ohio State University
J. P. Heppner, Naval Research Laboratory
H. H. Hess, Princeton University
R. E. Holzer, University of California, at Los Angeles
H. R. Joesting, U. S. Geological Survey
J. W. Joyce, National Science Foundation
J. Kaplan, University of California
D. G. Knapp, U. S. Coast and Geodetic Survey
G. P. Kuiper, Yerkes Observatory
H. E. Landsberg, U. S. Weather Bureau
G. G. Lill, Office of Naval Research
G. J. F. MacDonald, Massachusetts Institute of Technology
A. G. McNish, National Bureau of Standards
D. H. Menzel, Harvard College Observatory
C. L. Pekeris, The Weizmann Institute of Science, Rehovot, Israel
J. A. Peoples, Jr., Air Force Cambridge Research Center
R. G. Piety, Phillips Petroleum Company
F. Press, California Institute of Technology
F. W. Reichelderfer, U. S. Weather Bureau
R. R. Revelle, Scripps Institution of Oceanography
D. A. Rice, U. S. Coast and Geodetic Survey
E. B. Roberts, U. S. Coast and Geodetic Survey
W. O. Roberts, High Altitude Observatory, Colorado
W. W. Rubey, U. S. Geological Survey
P. A. Scherer, Carnegie Institution of Washington
G. F. Schilling, U. S. National Committee, IGY
R. J. Seeger, National Science Foundation
M. M. Shapiro, Naval Research Laboratory

- A. H. Shapley, National Bureau of Standards, Colorado
J. A. Simpson, University of Chicago
L. B. Slichter, University of California
W. E. Smith, American Geophysical Union
I. S. Sokolnikoff, University of California
V. P. Starr, Massachusetts Institute of Technology
H. K. Stephenson, National Science Foundation
H. Stommel, Woods Hole Oceanographic Institution
R. Stoneley, Department of Geodesy and Geophysics, Cambridge, England
H. E. Suess, Scripps Institution of Oceanography
H. E. Tatel, Department of Terrestrial Magnetism, Carnegie Institution of Washington
G. R. Tilton, Department of Terrestrial Magnetism, Carnegie Institution of Washington
M. A. Tuve, Department of Terrestrial Magnetism, Carnegie Institution of Washington
H. C. Urey, University of Chicago
J. Verhoogen, University of California
E. H. Vestine, Department of Terrestrial Magnetism, Carnegie Institution of Washington
J. von Neumann, Atomic Energy Commission
A. Waterman, National Science Foundation
H. W. Wells, Department of Terrestrial Magnetism, Carnegie Institution of Washington
G. W. Wetherill, Department of Terrestrial Magnetism, Carnegie Institution of Washington
H. Wexler, U. S. Weather Bureau
G. P. Woollard, University of Wisconsin
O. R. Wulf, U. S. Weather Bureau, California Institute of Technology
H. S. Yoder, Jr., Geophysical Laboratory, Carnegie Institution of Washington
A. Zmuda, Applied Physics Laboratory, Johns Hopkins University

NOTICE

When available, single unbound volumes can be supplied at \$6 each and single numbers at \$2 each, postpaid.

Charges for reprints and covers

Reprints can be supplied, but prices have increased considerably and costs depend on the number of articles per issue for which reprints are requested. It is no longer possible to publish a schedule of reprint charges, but if reprints are requested approximate estimates will be given when galley proofs are sent to authors. Reprints without covers are least expensive; standard covers (with title and author) can be supplied at an additional charge. Special printing on covers can also be supplied at further additional charge.

Fifty reprints, without covers, will be given to institutions paying the publication charge of \$8 per page.

Alterations

Major alterations made by authors in proof will be charged at cost. Authors are requested, therefore, to make final revisions on their typewritten manuscripts.

Orders for back issues and reprints should be sent to Editorial Office, 5241 Broad Branch Road, N.W., Washington 15, D.C., U.S.A.

Subscriptions are handled by The Editorial Office, 5241 Broad Branch Road, N.W., Washington 15, D.C., U.S.A.

JOURNAL OF GEOPHYSICAL RESEARCH